Tasmanian Institute of Agriculture

Impact of Clear Polymer Film on the Growth and Physiology of Maize

By

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March, 2019

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Table of Contents

Table of Contents

Table of Figures

List of Tables

List of Abbreviations

ABA	Abscisic Acid
APSS	Agricultural Production System Simulators
CHO	Carbohydrate
DCP	Degradable Clear Polymer Film
DM	Dry matter
DUL	Soil Water Content Drained Upper Limit (10 kPa extraction pressure)
EBA	Ethylene-butyl Acrylate
EVA	Ethylene-vinyl Acetate
F_0	Baseline leaf fluorescence
Film	Non-perforated clear polymer film
F_m	Maximal leaf fluorescence
F_v	Variable leaf fluorescence
$F_{v/m}$	Ratio of variable leaf fluorescence to maximal leaf fluorescence
g_0	Light Compensation Point of Stomatal Activity
g_1	Linear Slope Coefficient of Stomatal Activity
J_{max}	Rate of electron transport
K_m	Michaelis-Menten coefficient for Rubisco kinetics
LDPE	Low Density Polyethylene
LL15	Soil Water Content Lower Limit (1500 kPa extraction pressure)
LLDPE	Linear Low Density Polyethylene
[OC]	Concentration of Organic Carbon
PAR	Photosynthetically Active Radiation
PAWC	Plant Available Water Content (Crop Specific)
PBS	Polybutylene Succinate
PLA	Polylactic Acid
PVC	Polyvinyl Chloride
RCC	Relative Chlorophyll Content
R_d	Dark respiration rate
RUE	Radiation Use Efficiency
SEM	Standard Error of the Mean
T_{diff}	Difference between Maximum and Minimum Daily Temperatures
T_{max}	Maximum Daily Temperature
T_{min}	Minimum Daily Temperature
UV	Ultra-violet
Vc_{max}	Maximum rate of Rubisco activity
WUE	Water Use Efficiency
Γ^*	Photosynthetic CO_2 compensation point

Abstract

This thesis investigates the suitability of degradable clear polymer film use to support the production of cold-sensitive crops in Tasmania. Film used in this manner is poorly understood and rarely practiced in Australia but is practiced more widely in cold regions of the northern hemisphere. There has been limited agronomic research conducted in the area of film use to assist crop propagation, and contemporary research efforts in this field focus almost exclusively on film chemistry, particularly in the areas of formulation, spectral properties and degradation rate. Authors currently working in this field instead primarily focuses on clear film use for solarisation in summer for weed/pathogen suppression, and the thermal and reflected spectral effects associated with opaque ‘mulch’ film use for weed suppression. In addition to these main areas, there is some exciting work being made coupling novel-spectral absorption properties with changes in rates of pest insect development, but to date this has been focused on greenhouse cladding materials and has not yet made the transition across to clear propagation film.

This thesis first explores the effects of film use upon temperature conditions and gaseous substrate composition within the film-enclosed growing area, as well as solar radiation transmission properties of film under Tasmanian field conditions. Film use reduced the transmission of solar radiation into the headspace by 20 % and increased the concentration of water vapour and CO_2 within the film-enclosed headspace. Film use was shown to increase maximum daily temperatures within the film-growing environment. Film use increased minimum daily temperatures by ~4°C between late spring and early autumn, but reduced minimum daily temperatures during other months. Maximum daily temperatures beneath film varied seasonally in response to solar radiation intensity and cloud shading, increasing temperatures by as much as 10 °C above ambient temperatures during winter and 40 °C above ambient temperatures during summer. Models of these environmental changes were developed from ambient climate data, and were incorporated into APSIM to estimate temperatures at other sites from historical climate data.

After discussing the climate effects of film use, this thesis explored the effects of film use upon the agronomy and physiology of maize (*Zea mays* L.), a C_4 model crop species and forage source that is sensitive to cold and frost. Film-enclosed chambers were developed to enable establishment and growth of seedlings under different headspace gas compositions. Use of film was shown to improve all aspects of maize seedling performance under cold

seasonal conditions. Film use in winter and early spring protected seedlings from exposure to frost and increased soil and air temperatures, leading to earlier, more uniform crop emergence, faster seedling growth, and improved photosynthetic performance. Increases in seedling chlorophyll content, CO_2 assimilation and solar radiation utilisation caused by film use had few persistent effects on maize seedling physiology following removal of the film enclosure. Film use was less beneficial under warmer conditions, causing seedlings to regularly experience acute heat stress when exposed to damaging supra-optimal headspace temperatures above 40 °C. Increased headspace CO_2 concentration ([CO_2]) had minimal effect on maize emergence, growth rate or leaf carbon assimilation.

Information from climate monitoring and physiology experiments was used to inform APSIM modelling to estimate the effect of the film on crop survival and yield in several scenarios. Modelling suggested the production of above-ambient temperature conditions beneath the film favoured earlier planting dates during winter and early spring, with later dates subject to potentially damaging supra-optimal temperatures. Optimal film use was shown to increase simulated maize forage productivity by 10-15 % above existing industry practices in coastal regions. In inland regions, incorporation of film into early-sowing systems greatly reduced maize exposure to frost and subsequent crop failure, and increased long-term crop yields by 7-10 % above existing industry practices. Yields from film-supported production systems reported in this thesis represent conservative estimates only, and potential increases in yield productivity achieved through film use may exceed those reported in this thesis.

The results from this indicate that installation of film can create conditions suitable for maize establishment during winter and spring in this cool temperate environment. Extension of the growing season permits flowering and embryogenesis, facilitates the use of longer-season cultivars in cold-affected areas, and enables crop growth to be realigned to better match temperate winter-spring dominant rainfall patterns. Adoption of this technology may improve dryland maize productivity in some cold-limited regions, and reduce seasonal water consumption for existing irrigated maize producers. These benefits may also promote maize cultivation outside of existing coastal production regions in Tasmania.

Chapter 1: General Introduction

The earliest pioneer of film plasticulture (hereafter called film) for agricultural production was Emmert (1957), who investigated the use of early polyolefin polymers as low-cost alternatives to glass and paper-derived mulches in greenhouse and row crop applications. The success and industry interest in this early pioneering work led to the rapid adoption of polymer film for commercial greenhouses, polytunnels, row covers and mulches. In turn, it promoted the development and commercialisation of film materials with novel solar radiation transmission and degradation properties that are better suited for agricultural application (Espi *et al.,* 2006; Kasirajan and Ngouajio, 2012).

1.1 Film Plasticulture Materials

Films are estimated to be applied to more than 4.2 Mha annually in Europe, and more than 7 Mha in China alone (Scarascia-Mugnozza *et al.*, 2011; Kasirajan and Ngouajio, 2012). The majority of film products used in agricultural production systems are manufactured from non-degradable polyolefin materials due to their desirable physical and optical properties, availability and low cost. Common film substrates include linear low-density polyethylene (LLDPE), low-density polyethylene (LDPE), polyvinyl chloride (PVC), ethylene-vinyl acetate (EVA), and ethylene-butyl acrylate (EBA) (Espi *et al.* 2006). In addition, a growing list of alternative biodegradable polymer materials being incorporated into agricultural films includes polylactic acid (PLA), polybutylene succinate (PBS), and starch-derived polymer materials to improve film biodegradability and reduce environmental pollution and contamination (Kasirajan and Ngouajio, 2012). In addition to these bulk polymer materials an array of other additives is incorporated into the polymer matrix during formulation. These additives include UV and thermal stabilisers, pro-degradants and colouring agents, as well as nucleating agents, plasticisers, and other performance additives which are added to improve mechanical properties and ensure film uniformity. The composition and properties of each of these additives is summarised by various authors including Loy *et al.,* (1989), Briassoulis *et al.,* (2004), and Espi *et al.,* (2006).

Once formulated, polymers are manufactured into films between 10-80 μm in thickness. This thickness range ensures sufficient lateral and horizontal shearing strength, puncture resistance and elasticity to avoid damage during mechanical installation, minimises unnecessary material costs, and provides sufficient thermal stability and environmental longevity to prolong field use (Espi *et al.* 2006). Following field installation, exposure to ultraviolet radiation, repetitive freezing and thawing, high temperatures and agrichemical inputs cause the film to become increasingly brittle and susceptible to abrasion, perforation, tearing and whitening (Dilara & Briassoulis, 1999). The speed of this degradation process is regulated by site conditions and formulation, with film breakdown typically varying from 1-3 months to 3-4 years (Espi *et al.,* 2006).

1.2 Physical Effects of Film Use

Installation of film reduces the transmission of soil and plant emissions of water vapour from the enclosed growing environment to the surrounding atmosphere (Sheldrake 1963; Rubin and Benjamin, 1984; Pan *et al.* 2003; Snyder *et al.,* 2015; Braunack 2015a, b). Reductions in water vapour transmission can increase soil moisture availability in the enclosed area throughout the growing season (Braunack 2015a, b) by enabling water vapour to re-condense and return to the soil each evening (Dubois 1978; Brown *et al.* 1991; Wang *et al.* 2005). These effects present possibilities for reducing drought stress incidence and yield losses during early crop growth (Zhou *et al.,* 2009), and may enable the commercial cultivation of higher value crops in areas that would otherwise be precluded due to insufficient seasonal water availability (Lisson *et al.,* 2010).

Film use also increases water availability in the inter-row spaces by intercepting and redirecting water landing on the film's surface (Wang *et al.,* 2004). Increased rainfall concentration alongside film strips and soil water conservation beneath the film area can also potentially be harnessed in low-rainfall areas or seasons to enable earlier sowing, improved and faster establishment and increased potential yield (Lisson *et al.*, 2010; Wang *et al.*, 2004). In perforated systems, some of this water may instead be redirected towards perforations or holes in the film covers, increasing water availability immediately around plants growing below.

Film use increases solar radiation attenuation and reduces radiation intensity (Loy *et al.* 1989; Vox and Schettini 2007). Reduction of solar radiation intensity can protect cold-sensitive crops from photoinhibition, but may reduce maximum rates of photosynthesis (Ortiz-Lopez *et al.*, 1990; Wilson *et al.*, 1995; Kingston-Smith *et al.*, 1997; Lu *et al.*, 2000; Ying *et al.*, 2000). Measurements of solar radiation transmitted by film by Vox and Schettini (2007) estimate solar radiation attenuation to be as high as 5% using thin (<30 μm) polymer films, and increases with increased film thickness. Once installed in a field environment, condensation formation on the film's lower surface form irregular convex prisms that greatly increase radiation reflectance and scattering (Jaffrin & Mahklouf, 1990). These droplets increase rates of solar radiation attenuation and reduce PAR transmission to an unknown level (Pieters *et al.*, 1997).

The potential for season-length manipulation under plastic films could enable producers to take advantage of increased rainfall during spring months and complete heat-sensitive crop development stages before onset of the extreme heat of summer (Wang *et al.*, 2004). In addition, season-length manipulation can enable crops to be harvested earlier to take advantage of seasonal price premiums (Manseur 1984; Lisson 2010), and to increase crop reliability in regions susceptible to low spring and autumn temperatures (Lamont 2005).

Installation of film over an enclosed soil environment also slows the movement of CO_2 between the enclosed headspace and surrounding atmosphere (Mao and Kurata 1997), causing CO_2 emitted by plants and soil microbes to accumulate within the enclosed growing area (Rubin and Benjamin, 1984). Many authors have reported enhanced photosynthetic performance and plant growth under elevated [CO_2] (e.g. Dubois 1978; Garnaud 1974; Brown *et al.* 1990; Bowes 1993; Tubiello *et al.* 2007). In film-based production systems, growth rates of young seedlings may increase in response to elevated headspace [CO_2] prior to film removal or *in situ* degradation (Lisson *et al.*, 2010).

Lastly, film use increases the concentration of water vapour in the enclosed headspace environment, releasing latent heat into the enclosed space during condensation. Film use also insulates enclosed plants from exposure to ice and snow, reducing damage to aerial plant tissues. During such events, ice crystals are prevented from coming into direct contact with plants growing in the enclosed growing area, reducing crop damage from ice-induced membrane disruption and tissue desiccation (Pearce 2001).

1.3 Potential Applications for Film in Cereal Production

Global research efforts to understand the effects of film use on growing area microclimate, crop physiology and agronomy have been limited. It is speculated that film may have potential applications that improve the productivity and/or sustainability of existing cereal production practices in Australia due to its microclimate-altering properties. These applications are discussed below.

1.3.1 Increasing Water Conservation

In enclosed systems, water vapour conserved within the headspace environment is able to trap water vapour losses until they recondense as water droplets on the underside of the film barrier (Li *et al.*, 2012; Yaghi *et al.*, 2013; Yang *et al.*, 2015; Braunack *et al.*, 2015). Furthermore, film strips laid over a crop will redirect rainfall and irrigation into perforations and non-mulched growing areas, increasing the effective water application rate. These changes enable agricultural producers to minimise water losses from the growing environment and receive maximum benefit from irrigation water supplied to crops (Schhahbazian and Iran-Nejad, 2006; Braunack *et al.*, 2015).

This approach is being widely trialled in China as a means of passively modifying environmental conditions to facilitate earlier sowing and maize establishment, and enable crops grown in these regions to complete drought- and temperature-sensitive development stages before the onset of warmer spring and summer temperatures (Li *et al.*, 2012; Yang *et al.*, 2015). This promising approach uses one or more layers of polymeric materials to increase soil moisture conservation throughout the growing season by reducing water evaporation from the soil surface. Using this approach, Zhou *et al.* (2009) observed significant benefits to crop yield and water-use efficiency (WUE) in semi-arid regions of China, with optimal use of clear polymer films increasing crop WUE up to 11-fold.

1.3.2 Increasing Growing Temperatures in Cold-affected Regions

Polymer films are frequently used for manipulating temperatures within the growing environment (Kasirajan and Ngouajio, 2012; Scarascia-Mugnoza *et al.*, 2004; Espi *et al.*, 2006). Due to their customisable spectral properties, polymer films can be used to manipulate transmission and absorbance rates of solar and terrestrial radiation (200-2500nm wavelength). In polymer-free growing environments, incident solar radiation is absorbed by the soil unless intercepted by plant tissues. If plants are present, the leaves may intercept and absorb some of the incident solar radiation for continued photosynthesis and carbon assimilation, with remaining solar radiation reemitted into the headspace environment (Seginer, 1994). Radiation absorbed by the soil is converted to thermal energy and reemitted as longer-wavelength terrestrial radiation (Dubois, 1978). A proportion of this energy diffuses through the soil by conduction towards cooler soil material beneath, whilst the remaining thermal energy diffuses into the air above the soil and moves out of the growing area by convection.

Enclosing the growing environment with clear polymer films in the form of greenhouses, polytunnels or row covers (Kasirajan and Ngouajio, 2012; Espi *et al.,* 2006) reduces wind chill, obstructs air convection and reduces latent heat loss from the enclosed growing environment (Friend and Decoteau, 1990; Lamont, 1996). Furthermore, direct transmission rates of terrestrial radiation through this barrier are low (8-12%), slowing the conduction and diffusion of thermal energy and enabling heat to be retained within the enclosed environment. Clear polymer films are optically transparent to solar radiation, enabling solar radiation to enter the enclosed environment with little reflectance, absorption or scattering (Friend and Decoteau, 1990). Transmission rates through the film layer are between 85-95% of solar radiation under laboratory conditions (Vox and Schettini 2007; Lamont 2005), and somewhat lower under normal field conditions due to scattering and reflectance from water droplets on the film surface (Pollet *et al.* 2005).

The inclusion of opaque properties in the film is another way of passively regulating temperatures within the soil and plant canopy areas. Black and other dark-coloured opaque films effectively reduce growing surface albedo and increase solar radiation absorption, enabling increased heat generation and warming of the soil and canopy temperatures (Brown *et al.*, 1991). Conversely, the use of white, lightly coloured or highly reflective opaque films reduces solar radiation absorption and increases surface albedo (Brown *et al.*, 1990). This reduces thermal energy generation within these areas, enabling localised soil and canopy temperatures to be lower than the surrounding environment (Brown *et al.,* 1990).

Film is widely used for heating the enclosed headspace and soil environment in the European Union, Canada, and the United States when growing area temperatures are cold (Phipps 1994; Scarasscia-Mugnozza *et al.* 2011). This use of film technology can enable agricultural producers to sow and establish cold- and frost-sensitive crops and cultivars during periods of cold ambient temperatures, extending their effective growing season. This approach is widely used for forage maize production in the northern hemisphere to improve crop yield, dry matter yield and starch content (Crowley 1998; Kwabiah 2003; Easson and Fearnehough, 2000). For US sweet corn producers, film is estimated to increase financial returns through improved yield and quality by approximately $1700-7902/ha (Mansour 1984). Several authors have also identified other agronomic benefits from the use of clear agricultural polymer films in cold-temperate regions, including advancing crop development and harvest dates (Mansour 1984; Crowley, 2008; Easson and Fearnehough, 2000; Lamont 2005). Advances in harvest dates offer significant yield security benefits for maize growers in colder production regions, where maize quality and yield are threatened by the onset of early-season autumnal frosts (Kwabiah 2003; Crowley 1998; Pembleton and Rawnsley, 2012).

1.3.3 Insect & Virus Management

In addition to management of weeds and soil-borne fungi, polymer films can also be used to assist with the management of herbivorous insect pests (Espi *et al.* 2006; Diaz and Fereres, 2007). When present in high numbers, these pests can adversely affect crop health, productivity and yield, and act as transmission vectors for many plant viruses including barley yellow dwarf virus (Family Luteoviridae, Genus *Luteovirus*), cucurbit yellowing stunt disorder virus (Family Closteroviridae, Genus *Crinivirus*), zucchini yellow mosaic virus (Family Potyviridae, Genus *Potyvirus*), tomato yellow leaf curl virus (Family Geminiviridae, Genus *Begomovirus*) and tomato spotted wilt tospovirus (Family Bunyaviridae, Genus *Tospovirus*) (Raviv and Antignus 2004). In addition to losses of productivity, insects can reduce the market acceptability and value of agricultural and horticultural crops by causing visual blemishes, direct herbivorous damage and contamination of fruit and other saleable plant organs (Lamont 2005).

In greenhouses, polytunnels and other enclosed production systems, large populations of these insects can develop rapidly in response to sheltered conditions, increased temperatures and reduced predator access. In polymer film-enclosed systems, pressure from insect pest species including aphids (*Aphis gossypii* (Kumar and Poehling 2006), *Macrosiphum euphorbiae (Thomas), Acyrthosiphum lactucae (Passerini)* (Diaz *et al.* 2006)), thrips *(Ceratothripoides claratris* (Kumar and Poehling 2006), *Frankliniella occidentalis* (Diaz *et al.* 2006; Costa and Robb 1999)) and whitefly (*Bemisia tabaci* and *B. argentifolii* (Kumar and Poehling 2006; Costa and Robb 1999; Mutwiwa *et al.*, 2005)) can be reduced when constructed from UV-opaque (280-400nm) transparent materials. Use of these materials reduces the visual stimuli reaching the ultraviolet-sensitive visual and development photoreceptors of many insect species, leading to direct reductions in herbivory, insect pressure, and development rates (Shimoda and Honda 2013).

Reflective and coloured films can also reduce herbivorous insect pressure on crops in non-enclosed systems. Highly reflective films achieve this by using reflected solar radiation to overstimulate the photoreceptors of insect species, masking the presence of plants and reducing the ability of passing insects to locate and identify host plants growing in close proximity. Similar effects also have been achieved by using coloured film to alter visual stimuli received by insects. This change in visual stimuli can help mask the presence of potential crop host plants, reducing browsing damage and the spread of insect-borne viruses from some travelling insect pests (Antignus 2000; Raviv and Antignus 2004).

1.3.4 Management of Herbicide-Resistant Weeds

Weed infestations in crop-growing areas adversely affect crop productivity and market acceptability by causing contamination and reduced crop yield. Early weed competition for limited solar radiation and soil water resources can greatly reduce crop density and growth rates during vegetative growth. In conventional Australian agricultural systems, management of weeds is reliant on the use of herbicides, which are progressively being challenged by increasing numbers of herbicide-resistant weed species (Rubin and Benjamin, 1984). For these reasons, polymer films with targeted spectral transmission properties are being increasingly adopted in agriculture to assist with the management of a diverse array of weed pest species (Kasirajan and Ngouajio, 2012; Scarascia-Mugnozza *et al.*, 2011, Espi *et al.,* 2006).

One approach for using film to control weeds within the enclosed growing area is solarisation during crop fallow periods. This process utilises the heat-trapping properties of clear polymer films to elevate headspace and surface soil temperatures beyond thermal thresholds of weed seeds and soil-borne pathogens during summer fallow periods (Brown *et al.,* 1991; Stapleon and DeVay, 1986). Film solarisation has been adopted in Israel, Europe and the USA to assist with the management and disinfestation of weeds and pathogens from productive cropping soils, reducing crop rotation lengths and enabling increased production of high-value crops (Rubin and Benjamin, 1984; Brown *et al.* 1991; Chase *et al.*, 1999).

Another form of film-based weed control is the use of opaque mulch films (Kasirajan and Ngouajio, 2012). These films are installed as soil overlays following cultivation and seed bed preparation, and remain installed in the field until after crop maturity and harvest, where they intercept photosynthetically active radiation (PAR) before it can be used by plants (Loy *et al.,* 1989; Scarascia-Mugnoza *et al.*, 2011). Following installation over the growing area, small regularly spaced areas can be excised from the mulch film layer for crop planting, enabling unhindered crop growth in the planted area whilst leaving the inter-plant area covered beneath the film layer. These mulch films are typically anchored to the ground by burying the edges of the film with soil within narrow bed systems (<1.2 m). In some areas susceptible to high winds, additional protection against wind damage in the form of wire stakes may also be required. This is considered highly beneficial by growers of low or prostrate-growing crop species, which might otherwise quickly become shaded by grasses and other tall weed species growing in the inter-plant space and contaminated by weed trash (Rosa-Ibarra *et al.*, 2005).

1.3.5 Soil Protection from Erosion

Enclosing the growing environment beneath polymer films can assist with conserving the structural and hydraulic properties of soils at risk of erosion. Such soils are considered fragile due to their susceptibility to particulate fracture and structure loss, which can be exacerbated by raindrop water bombardment, rilling and sodicity-induced dispersion (McClaren and Cameron 2008). Installation of transparent polymer film above the growing environment enables incoming rainfall to be intercepted and redirected towards catchment and drainage regions (Römkens *et al.*, 2002). Areas enclosed by this layer are protected from high-velocity raindrop bombardment, minimising pedal fractures which promote surface crusting and obstruct pores in the soil structure responsible for water infiltration, redistribution and storage (McKeague, 1997). This protection can be valuable when other forms of soil surface cover are minimal, including initial crop establishment and early leaf growth (Moss 1991). Polymer film enclosure also offers some protection from wind erosion of cropping soils. Reductions in wind erosion are caused by enclosure and isolation of the growing area soil beneath the polymer film layer and by creating an uneven surface topography that can trap and accumulate wind-borne soil particles (McKeague 1997). In combination, these two properties disrupt the chain reaction of particle collisions and saltation caused by wind erosion.

1.4 General Physiological Responses of Cereal Crop Species to Climate-based Abiotic Stresses

In Australia, seasonal climate and soil conditions can expose crops to a variety of abiotic stresses throughout crop growth. These stresses can include drought, heat, cold, frost, waterlogging, salinity, sodicity, water quality, either individually or in combination (Birch *et al.*, 2006). Crop yield is negatively influenced by exposure to these stresses, with plant sensitivity varying in response to the duration and severity of stress exposure and crop ontogenic development stage (Yadav 2010). As discussed in Section 1.4, judicious use of film may reduce crop exposure to some climate-based abiotic stresses, alleviating some of the problems described below.

1.4.1 Drought Stress

The biggest constraint on dryland cereal production in many Australian production regions is seasonal rainfall variability and drought stress (Birch *et al.* 2003). In Australia, geographic and seasonal factors have a strong influence on the frequency and intensity of natural rainfall events. Temperate regions in southern New South Wales, Victoria, Tasmania, South Australia and southern Western Australia have winter/early spring-dominant rainfall patterns. By contrast, tropical regions in northern New South Wales, Queensland and the Northern Territory typically experience intense regular precipitation events during the summer and early autumn months (Gordon *et al.*, 2016). Dryland production systems rely on these natural precipitation events to replace water lost due to evaporation and crop transpiration emissions (Gordon *et al.*, 2016). Without regular recharge, water reserves in the soil become depleted and require the expenditure of increasing amounts of metabolic energy for extraction and use by crop plants, leading to drought stress (Barnabas, 2008).

Drought stress has an inhibitory effect on cereal productivity. In general, even mild drought stress reduces biomass production by limiting individual leaf area and total plant leaf area index, thereby limiting the effective area for light interception and photosynthesis (Chenu *et al.*, 2008). Mild drought stress also decreases stem elongation and promotes deeper root growth, promotes carbohydrate partitioning towards root growth and reduces rates of leaf and stem growth (Sharp and Davies, 1979; Barber *et al.*, 1988; Kuchenbuch and Barber, 1988). Increasing the severity of this drought stress also stimulates the synthesis and translocation of the stress phytohormone abscisic acid (ABA) throughout the plant, stimulating stomatal closure (Aroca *et al.*, 2012). ABA-mediated stomatal closure prevents direct water transpiration through the stomata, greatly reducing plant water diffusion between plant tissues and the surrounding headspace environment (Farquhar and Sharkey, 1982; Collatz *et al.*, 1991; Collatz *et al.*, 1992).

In addition to the primary effects of water shortage, prolonged drought-induced stomatal closure can also have negative secondary effects on crop photosynthesis and carbohydrate production (Farquhar and Sharkey, 1982; Barnabas *et al.*, 2008). In addition to limiting water movement, stomatal closure prevents the diffusion of CO_2 from the surrounding atmosphere into photosynthesising plant tissues. This causes depletion of dissolved [CO_2] within the chloroplast, interrupting carbon fixation, carbohydrate production and photorespiration (Collatz *et al.*, 1992). During flowering and anthesis, embryogenesis then competes with other basic maintenance processes for carbohydrates to produce ATP (Barnabas 2008). As an energy-consuming metabolic pathway, CO_2 shortage is particularly detrimental during this period because it exacerbates cellular competition for ATP and NADPH produced during glycolysis and cellular respiration (Barnabas *et al.* 2008). This competition leads to reduced embryo survival and increased zygote abortion, permanently reducing the potential grain number, seed density, grain quality and crop yield potential of cereals (Hawkins and Cooper, 1981; Maddonni *et al.*, 1998).

1.4.2 Heat Stress

In Australia, many crop species are susceptible to heat stress from excessive air and soil temperatures during key critical stages of early vegetative and reproductive development. Heat stress during this period reduces reproductive fertility in affected plants (Cheikh and Jones 1994, Barnabas *et al.*, 2008), but can be partially reduced through crop irrigation to encourage plants to transpire water and cool themselves through water evaporation (Costa *et al.*, 2013). This extension of the irrigation season increases production costs and decreases water use efficiency (Yin *et al.*, 2014).

Water stress and prolonged stomatal closure also exacerbate plant heat stress. Prolonged stomatal closure reduces water evaporation from and vapour diffusion in leaf tissues, reducing latent heat dissipation (Barnabas *et al.*, 2008). In warm environments, cessation of this passive cooling mechanism can cause temperatures in aerial plant tissues to increase significantly (Costa *et al.*, 2013). During reproductive development stages, this additional heat can cause tissue temperatures to exceed optimal temperatures, causing heat stress (Barnabas *et al.*, 2008). If occurring during anthesis or seed filling, this additional heat stress can exacerbate the effects of drought stress and competition for carbohydrate.

1.4.3 Cold Stress

In regions of Tasmania, Victoria, South Australia and southern New South Wales, seasonal air and soil temperatures are frequently cool (< 15°C) throughout spring and autumn. During early growth, seasonal air and soil temperatures during winter are less than optimal for cereal production, causing seedlings to develop slowly (Birch *et al.*, 2003). Ambient soil and air temperatures directly regulate the speed of enzyme velocity and metabolic reaction kinetics which govern rates of seedling emergence, carbon assimilation, biomass production and plant development (Walker, 1969; Creveceour *et al.*, 1983; Stone *et al.*, 1999). During germination and seedling emergence, exposure to low temperatures results in poor germination and delays in crop emergence. These processes are strongly regulated by soil temperature (Mahan 2000). As plants transition towards reproductive growth and leaf production, cold stress can result in stunting, reduced leaf and root expansion, and leaf chlorosis (Farooq *et al.*, 2009). Reductions in leaf area and chlorophyll density limit solar radiation interception and photon harvesting, whilst reductions in root length can limit the surface area and ATP availability for uptake of dissolved nitrogen, phosphorus and other mineral nutrients (Yadav, 2010).

For tropical cereals like maize and sorghum, exposure to low (< 10-15°C) seasonal temperatures can cause a variety of issues during all stages of seedling development. Cold stress in tropical cereal species reduces photosynthetic efficiency and increases susceptibility to photoinhibition by reducing enzyme velocity for carbon fixation and limiting electron movement through photosystems I and II (Lutz, 2010). This inhibition promotes secondary photooxidative stress under periods of high photon density, as harvested photons form damaging reactive oxygen species within the chloroplast instead of being transferred by photosystems I and II (Farooq *et al.*, 2009). During frosts and other extreme cold-weather events, cold stress-induced dehydration can also cause direct damage to the plasma membrane of affected tissues, resulting in localised necrosis in tissues subjected to frost (Steponkus 1984). The use of short-season hybrid varieties with increased cold tolerance is a common practise to reduce the likelihood of crop planting dates being delayed excessively by unseasonably cool seasonal temperatures (Birch *et al.*, 2003).

Cold stress during anthesis and flowering also delays maize heading and increases pollen sterility, reducing grain yield and cob quality at harvest. In warm-temperate cereals like rice and tropical cereals like maize and sorghum, this is linked to damage to the pollen plasma membrane (Suzuki *et al.,* 2008) caused by cold stress-induced dehydration and membrane crystallisation (Steponkus 1984). These issues can be exacerbated by cold stress during autumn, which slows grain filling and reduces harvest yields (Farooq *et al.*, 2009). Like early vegetative growth, yield losses during this period are caused by reduced carbon assimilation, photoinhibition and photooxidative damage to leaves and other photosynthetic tissues (Barnabas *et al.,* 2008). In addition, cold temperatures during this period can slow rates of development; this can expose late-planted crops to increasingly cold temperatures, and increases the risk of the crop becoming damaged by early seasonal frost events (Crowley, 1998; Pembleton and Rawnsley, 2012). Common effects caused by maize silage exposure to frost include poorer fermentation characteristics, reduced livestock digestibility, decreased potassium, nitrogen, phosphorus and calcium content, and increased pH and dry matter content compared to non-frosted maize (Narasimhalu *et al.* 1986; St Pierre *et al.*1983). Film use represents a technology for ensuring earlier harvest and reduced exposure to potentially damaging frost events.

1.5 Options for Managing Cereal Abiotic Stress in Australia

Uncertainty over the effects and benefits of film use have limited uptake of film use in Australia. This uncertainty has prevented adoption of film plasticulture practices by cereal producers in Australia (Lisson *et al.,* 2010, Braunack *et al.*, 2015).

Today, modern agricultural producers must rely on other tools to manage and moderate the effects of drought, heat and cold stresses. These tools include cultivar selection, planting date selection, environmental insulation, and strategic irrigation use.

1.5.1 Cultivar selection

Cultivar selection is one of the primary tools used to manage abiotic stress in Australian cereal crops. In dryland production systems, optimal cultivar selection can depend on seasonal rainfall and temperature outlook, timing and amount of rain at sowing, as well as the water storage capacity of the soil (Birch 1997). In regions with high temperatures and limited recharge capacity from seasonal rainfall, use of early-maturing cultivars is advised to reduce the risk of acute drought stress occurring before crop maturity (Birch *et al.*, 2006). In contrast, use of later-maturing cultivars may be advantageous in irrigated systems to prolong opportunities for grain filling and crop yield (White, 1978). For example, in maize, maturity lengths for these varieties can also vary significantly, with most available varieties maturing between 95 to around 135 days CRM (comparative relative maturity) (Löffler *et al.*, 2005).

1.5.2 Planting Date Selection

Manipulation of planting date is used by many cereal producers to avoid climate-based abiotic stresses (Ramankutty and Foley, 1998; Monfreda *et al.*, 2008; Sacks *et al.*, 2010). In northern Australia, cereal production can be constrained by summer heat stress (WA DAF 2015). In these regions, planting dates are often adjusted to minimise the risk of supra-optimal temperatures occurring during crop pollen set, anthesis, and embryogenesis.

In central and southern Australia, maize planting dates are selected to maximise growing season length whilst minimising the risk of crop exposure to frost, cold and drought. Wheat, barley and oats are typically planted during winter and early spring to maximise crop access to winter and spring rainfall (Gordon 2016). Frost-sensitive temperate tropical cereals such as rice, maize and sorghum can safely be planted as early as mid-October in warmer regions of New South Wales, Victoria and South Australia (Garcia 2012). These planting dates are frequently deferred until early-mid November in colder regions of Victoria and parts of Tasmania due to cold temperatures and prolonged frost risks during spring (Pembleton and Rawnsley 2012). Film use in these areas may increase growing season temperatures and shelter crops from seasonal frost events, enabling earlier planting dates and extending the effective growing season (Lisson 2016).

1.5.3 Irrigation

Irrigation is a commonly used tool for managing seasonal drought and heat stresses, where available. Irrigation enables direct recharge of soil moisture reserves depleted by soil deep drainage and crop growth. Increasing soil moisture availability has been shown to increase the transpiration rate of many cereal species, enabling greater latent heat loss (Costa *et al.*, 2013). In addition, increasing soil moisture, diurnal heat diffusion, latent heat capacity and throughout the soil, reducing soil temperatures and crop heat stress in root tissues (Deltour *et al.*, 1985).

One of the limitations to irrigation use is that irrigation water is not available in many dryland regions of Australia, and crops are reliant on summer and autumn rainfall to replenish soil water reserves. Cereal crops can vary greatly in the volume of water needed for drought and heat stress management (e.g. up to 7-9 ML for maize during summer; Birch *et al.,* 2003). In regions and seasons where water availability and/or water prices preclude intensive use of irrigation water, irrigators are more selective with the timing of irrigation water applications (Birch *et al.,* 2003; Conaty 2010). In these circumstances, irrigation water is preferentially applied around flowering and grain filling to maximise grain set, carbon assimilation and grain weight (Barnabas *et al.*, 2008). Combining this approach with film use is likely to reduce water consumption rates (Braunack 2015) and crop exposure to drought stress, thereby increasing crop productivity and WUE (Wu *et al.*, 1996).

1.6 Thesis Objectives & Hypotheses

Limited contemporary agronomic research has been conducted in the area of film use to assist crop propagation. Developments in film systems have primarily resulted progresses in polymer materials sciences for greenhouse cladding materials, including (a) advances in film chemistry, particularly in the areas of formulation, spectral properties and degradation rate; (b) improved capacity to manipulate the thermal and reflected spectral effects associated with opaque 'mulch' film use for weed suppression; and (c) adoption of clear films for solarisation in summer for weed/pathogen/insect suppression, and (d) the use of photosynthetic radiation blocking to disrupt pest insect development.

This thesis seeks (1) to determine the microclimate effects of film use in Tasmania, and (2) to evaluate the suitability of film use for improving long-term productivity in cereal production. The suitability of films in cereal production is dependent on the film's capacity to create environmental conditions favourable for crop growth. In this thesis it is hypothesised that optimal film use can increase the long-term productivity of selected cereal crops. This thesis aims to test this hypothesis by developing a biophysical model of the headspace microclimate caused by film use (in relation to solar radiation, headspace gas composition and temperature conditions), then using this model to provide quantitative estimates of the benefits and risks associated with film by answering the following research questions:

1 Can film use reduce crop stress caused by cold and frost?

2 Do seasonal increases in headspace temperature cause seedlings to experience heat stress?

3 Are warmer soil and air temperatures under film suitable for the establishment of temperate and/or tropical cereals? When is the most appropriate time for film to be used?

4 Does enrichment of headspace [CO_2] in film-enclosed environments increase rates of seedling photosynthesis, growth and sensitivity to heat stress?

5 Can optimal film use increase the long-term simulated productivity of selected cereals in inland and/or coastal regions in Tasmania?

One limitation to the development of a biophysical model is the lack of quantitative information about microclimate conditions within the film-enclosed headspace. Currently, very little is known about microclimatic conditions in film-enclosed growing environments under Tasmanian or mainland Australian conditions. Other sources of information about the microclimate effects of film use are limited, fragmented, contextualised, and often conflicting. For this reason, quantitative answers are needed for the following questions before a biophysical climate model for film-enclosed headspace can be developed:

1 What are the temperature increases caused by film use in Tasmania? How do they vary in response to seasonal environmental changes?

2 Does soil moisture content influence heat accumulation and storage beneath film?

3 Is [CO_2] within the enclosed headspace would be higher than ambient concentrations? Does [CO_2] fluctuate in response to changes in temperature and light availability?

4 How does film use influence headspace relative humidity (RH) and vapour pressure deficit (VPD)?

5 How does film use influence solar radiation intensity and exposure within the film-enclosed environment? Does solar radiation transmission through film vary seasonally? If so, what causes these changes?

To address each of these topics in sufficient depth, this thesis has been divided into six experimental chapters which are briefly described as follows:

Chapter 2

The objectives of this chapter were to investigate: (1) how film use influences temperature, atmospheric composition and solar radiation conditions within the enclosed headspace environment; and (2) how these conditions are influenced by key ambient site and climate variables.

Chapter 3

This chapter aimed to: (1) develop a biophysical model of headspace temperature and solar radiation within film-enclosed environments; and (2) incorporate this model in APSIM to investigate seasonal temperature and frost risks for different Tasmanian locations.

Chapter 4

This chapter describes the design and engineering of a self-recording network of film-enclosed growing chambers developed to enable controlled plant growth and physiological monitoring under the dynamic environmental processes and mass-energy fluxes described in Chapters 2 and 3.

Chapter 5

This chapter reports on the effects of film-based increases in headspace temperature and [CO_2] on the photosynthetic physiology and agronomic development of maize, a tropical C_4 cereal model species which is widely used by industry.

Chapter 6

In this chapter, APSIM is used in conjunction with historical climate records to establish cold and frost incidence and the related impacts on crop failure rate, crop development, and crop productivity for a tropical cereal (maize) grown for forage and grain at seven sites throughout Tasmania.

Chapter 7

This chapter reports the results of a systems modelling study into interactions between film use, planting date, and cultivar genotype on silage maize development, productivity and security at harvest across four sites in Tasmania.

General discussion and general conclusions are described in chapters 8 and 9 respectively.

Chapter 2: The Effect of Film on Headspace Microclimate

2.1 Abstract

Film use has been proposed for season-length manipulation in Tasmania and other temperate areas of Australia. Currently, film is not used commercially in most of Australia, and little is known about how this technology will influence growing conditions in the Tasmanian environment. An experiment was established using four different soil types at two sites near Clifton Beach and Cambridge in southeast Tasmania to quantify temperature and microclimate changes caused by film use. The experiment was run for 12 months to capture a wide range of ambient climate and related conditions. Enclosure with polymer film row covers altered temperature conditions within the film-enclosed environment. Temperatures within the enclosed headspace environment were highly variable and were influenced by short-term changes in ambient temperature and solar radiation intensity. Maximum daily temperatures in the headspace were largest in the dry silt soil treatment. Headspace [CO_2] rapidly rose above ambient atmospheric levels (~400 ppm), reaching a maximum of approximately 40,000 ppm (~4 %). Headspace vapour pressure deficit (VPD) increased and relative humidity (RH) decreased during daylight periods due to changes in saturation point and water content. Solar radiation transmission through the film varied with soil type but showed minimal seasonal variation and was not influenced by headspace temperature, relative humidity, or VPD.

2.2 Introduction

Use of film has been proposed for season-length manipulation in temperate areas in the cereal industries in Australia. Recent field trials have shown that use of polymer film row covers can be used in Australia for cotton production to enable earlier sowing, establishment, and maturation (Brown 2014; Braunack 2015), suggesting that use of this technology may be adaptable for other tropical crops grown in Australia.

Film use is not practiced commercially in most of Australia, and little is known about how this technology will influence growing conditions in the Australian environment. Due to reliance on radiation transmission properties for heat retention, the thermal effects of row covers use is expected to vary with location, time of year, soil type and polymer film characteristics (Mahrer 1979). In colder seasons and climates, temperature increases beneath the polymer row covers would be expected to generally promote growth and development, provided such increases do not approach or exceed critical temperatures for plant growth (Stone *et al.,* 1999; Easson and Fearnhough, 2000). In hotter seasons and climates, these temperature increases may exceed optimal plant temperature ranges, promoting crop heat stress (Muchow, 1990) and possible plant death via solarisation (Katan *et al.*, 1976; Stapleton and DeVay, 1986; Gamliel and Katan, 2012). In this chapter, I report on investigations into: (1) how film use influences temperature, atmospheric composition and solar radiation conditions within the enclosed headspace environment; and (2) how these conditions are influenced by key ambient site and climate variables. In subsequent chapters, these relationships are used to develop simple generic models for predicting headspace climate variables from historical climate data, and how these models can be combined with site-specific environmental data for use in agricultural system models including APSIM (Keating *et al.* 2003).

2.3 Materials and Methods

2.3.1 Site location

An experiment was established in August 2013 on four different soil types at two sites near Clifton Beach (42.59°S, 147.31°E) and Cambridge (42.79°S, 147.42°E) in southeast Tasmania. The experiment was run over 12 months to capture a wide range of ambient climate and related conditions (e.g. sun angle, day length) necessary for model development. Site locations were chosen to incorporate soils with a range of physical, chemical and biological properties (

Table 2.1). After initial establishment, the experiment was temporarily ceased during mid-summer (10 January to 1 March 2014) during which period the maximum temperatures under the film were above the recommended operating limits of the sensors. Furthermore, while the experiment did not include plants, diurnal headspace temperature fluctuations during this period were well above known maximum crop growth thresholds and were subsequently considered unnecessary for inclusion in the model.

Table 2.1 Selected attributes of soil treatments (courtesy SWEP Analytical Laboratories)

Soil number	1	2	3	4
Name	‘Sand’	‘Mudstone’	‘Sandy loam’	‘Clay’
Location	Clifton	Clifton	Cambridge	Cambridge
Surface Texture	Sand	Fine sandy light clay	Sandy loam	Heavy clay
Colour	Light grey	Greyish brown	Brown	Brownish grey
pH (water)	7.0	5.6	5.6	7.1
Organic carbon (%)	Nil	2.4	1.5	3.2
Organic matter (%)	Nil	4.7	3	6.3

2.3.2 Site preparation

At each site, strips of soil (~4 m long × 2 m wide) were cleared of weeds and tilled uniformly in a north/south orientation to a depth of ~40 cm. The soils were wetted artificially to field capacity where necessary before being shaped into a low mound. The relative surface ‘roughness’ and porosity of these mounds varied with soil structure and the amount of space between surface aggregates due to variations in soil aggregate pedality, uniformity and size. This surface roughness was smallest in the sand treatment that demonstrated unstructured ‘single grain’ pedality, and was significantly larger in the clay treatment whose ‘strong’ pedality created larger inter-aggregate pores and spaces. Such heterogeneity had minimal effect on non-enclosed treatment, but created some additional variability in the volume of air entrapped in polymer row covers-enclosed treatments.

Once formed, mounds were randomly allocated to either the non-enclosed control treatment or enclosed treatment. Film treatments were created by covering the mound with strips of a single UV-stabilised, clear polyethylene propagation film (3 m long × 1.2 m wide × 10 µm thick) manufactured and provided by Integrated Packaging Pty Ltd, Melbourne. Film was applied directly as an unsupported overlay directly over the soil, with the edges of this film overlay were covered with soil to a depth of ~15 cm to create a sealed headspace environment between the soil surface and the underside of the film, which was replaced every 3-4 months due to general wear and tear including bird damage, insect damage and film breakdown. Bird damage was more extensive and prolonged in the clay treatment resulting in a data gap from early December 2013 to early January 2014. During these film replacement events, soils at all sites were artificially rewetted to field capacity.

One of the main applications of the predictive models generated from the experimental results was to identify safe operational times for film use at a given location. These operational limits should reflect the most extreme headspace climate conditions, which correspond to bare soil without the moderating effect of plants on headspace temperature (Zhou *et al.*, 2009). To remove the confounding effects of variable plant growth on the headspace climate and broaden the genericity of the trial results, plants were not included in the trial. Film is typically in place for a limited amount of time during crop establishment when plants are small and the moderating effect on headspace climate is likely to be limited. Furthermore, plant growth under film is highly variable and can be influenced by a range of factors including species, time of year, soil characteristics, and moisture content. Indeed, for much of the year growth under clear polymer films is prevented by supra-optimal temperatures. For this reason, the impact of plants on the headspace climate would be highly variable and inconsistent over the 12-month duration of the experiment, and across the range of treatments imposed.

2.3.3 Sensors and data recording equipment

Solar radiation in this environment was measured with a pyranometer (SP110, Apogee, USA) covering the short-wavelength range of 360 to 1120 nm and a 180° field of view. In film-enclosed treatments the headspace pyranometer was placed 2 cm below the film in all treatments to prevent distortion due to direct contact between the sensor surface and film surface. Headspace air temperature and relative humidity were measured using a single combined sensor (CS 215 probe, Campbell Scientific, Australia) housed inside a 12 cm diameter louvered radiation shield. Temperature, radiation and relative humidity observations from these sensors were recorded for each treatment every 10 minutes and stored in a data logger (CR200X logger, Campbell Scientific, Garbutt QLD, Australia). Sensors monitoring climatic conditions within each film- and ambient-treatment were installed at surface soil height to directly monitor changes in solar radiation, surface air temperature, and relative humidity. Sensors located within the film-enclosed treatment were installed in a small depression to limit stretching and distortion of the film membrane around the sensor unit and to ensure air movement and condensation was able to take place between the film and pyranometer. An additional set of sensors was installed at a height of 1.2 m at each monitoring station to enable direct comparisons between site microclimatic conditions and weather observations reported by the Australian Bureau of Meteorology for these and other sites.

2.3.4 Ancillary Experiments

In addition to the primary climate modification experiment outlined in section 2.3.2, three ancillary experiments were undertaken. The first of these was constructed to quantify the effects of water vapour condensation on the film's lower surface on the transmission and attenuation of incident solar radiation. This ancillary experiment was established at the Clifton Beach site, with film was stretched over a custom plywood frame. This frame was shaped to replicate the curved profile and oriented to match the film surface orientation of the other soil treatments. An enclosed gap was incorporated into the design In accordance with conditions at other experiments, and the radiation pyranometer was similarly positioned 2 cm below the lower surface of the film. Airflow through this headspace area minimised the accumulation of vapour condensation on the surface of the pyranometer.

The second ancillary trial was established on the Cambridge sandy loam site to determine the effect of soil moisture content on headspace temperature and relative humidity. A second polymer film row treatment was established at this site at the end of summer. The top 40 cm of the profile was underlaid with a layer of dense polymer mulch film to prevent lateral and vertical influx of moisture from the adjacent rows. This 'dry' treatment was not rewetted during film replacement events, but in all other respects was managed identically to the 'wet' treatments at all sites.

The third ancillary experiment sought to gain an understanding of trends in the concentration of atmospheric CO_2 within the confined headspace environment. Atmospheric carbon dioxide concentrations were measured every 15 minutes using standalone, battery-powered logger/sensors (CM0019, www.co2meter.com, Florida USA) deployed for approximately seven-day periods across each of the soil treatments. Data from these sensors was logged to the device and downloaded prior to recording at the subsequent site.

2.4 Results

2.4.1 Fluctuation in Headspace Temperature

The polymer film row enclosures altered temperature conditions within the film-enclosed environment. Film had pronounced seasonal effects on diurnal temperature fluctuations for all soil types. Maximum daily temperatures were typically greater within the film-enclosed headspace treatment than within the non-enclosed environments across all soil treatments (Figure 2.1; Figure 2.2). Seasonal differences in maximum headspace temperatures varied, with the lowest differences (-1.4 °C) occurring in late May, and largest (39.8 °C) in early January (Figure 2.3). These changes were associated with seasonal changes in day and night length, influencing the amount of time available for heat diffusion before the onset of the next daily heating events. Maximum headspace temperatures were below ambient maximum temperatures on only four days throughout the period of observation (Figure 2.4a). These four days coincided with short day lengths, low incident radiation and significant light attenuation from condensation under the film, restricting the normal accumulation of heat within the headspace. In the mudstone treatment minimum daily temperatures typically increased by as much as 4 °C above ambient during summer months and were often 2-4 °C below ambient during other months (Figure 2.4b). Seasonal changes in daily temperature minima in the adjacent sand treatment were typically smaller (1-2 °C) than the mudstone treatment, indicating potential soil influences.

Temperatures within the enclosed headspace environment were observed to be highly variable and were strongly influenced by short-term changes in solar radiation intensity and ambient temperature. During winter, temperatures in the enclosed growing areas were observed to vary ± 7 °C hr^{-1} in response to changes in solar radiation, whilst temperatures within non-enclosed treatments varied by only 4 °C hr^{-1}. The difference in temperature response to fluctuating ambient conditions between enclosed and ambient environments increased to more than 15 °C hr^{-1} during summer in response to seasonal changes in solar radiation intensity and day length.

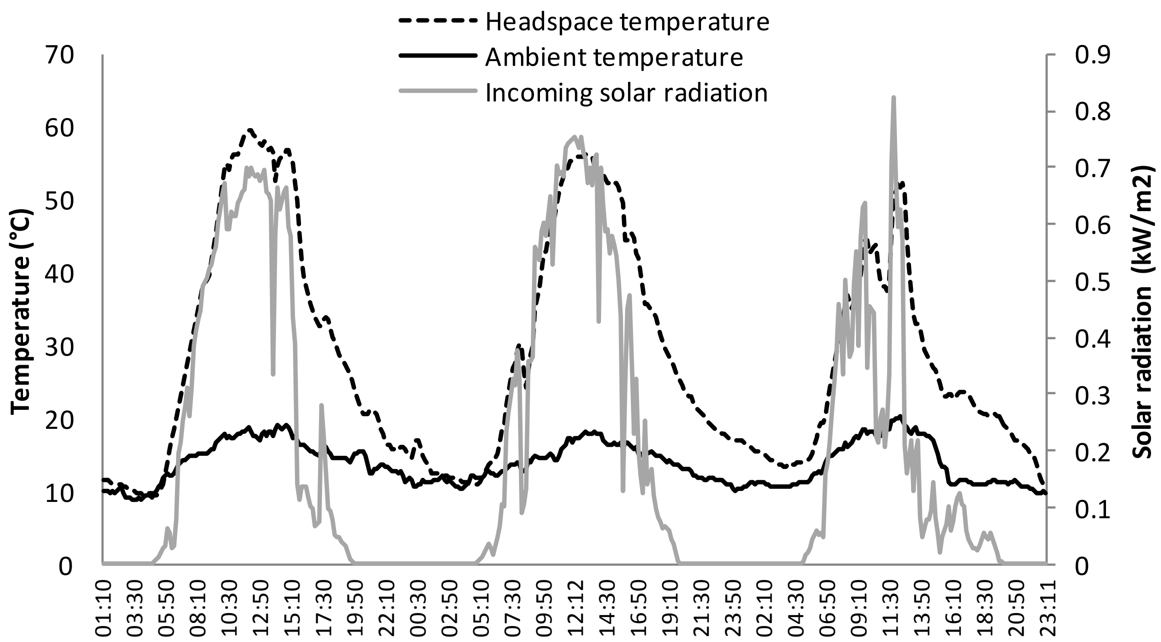


Figure 2.1 Headspace temperature and incoming solar radiation (five-minute intervals) over the three-day period from January 3 to January 5, 2014 for the mudstone soil treatment at the Clifton site.

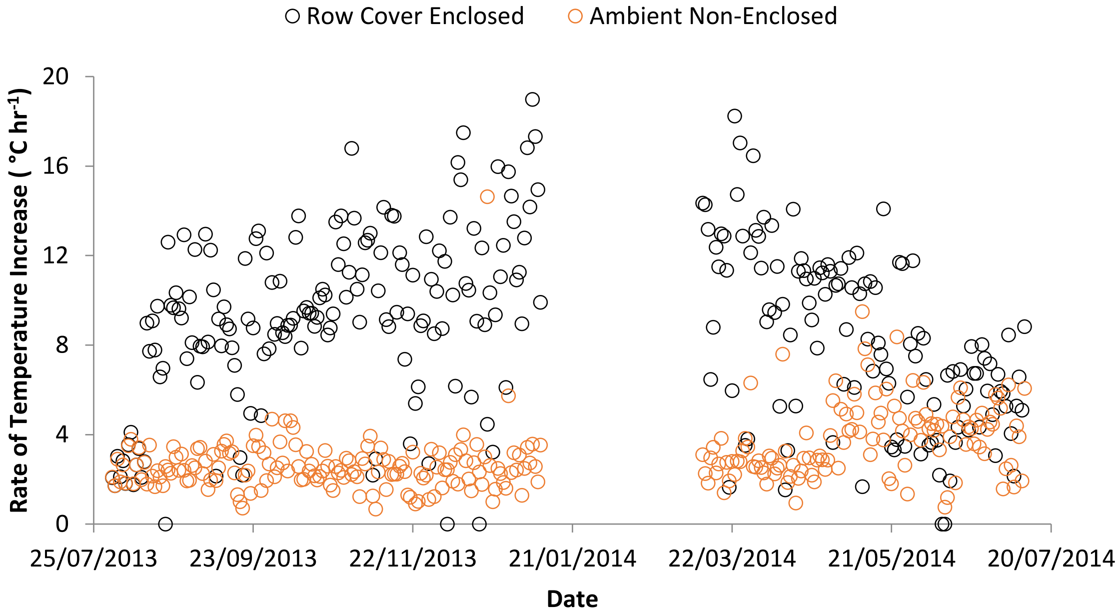


Figure 2.2 Maximum temperature increases within film-enclosed beds enclosed (Black) and ambient (Orange) within the mudstone soil treatment at Cambridge.

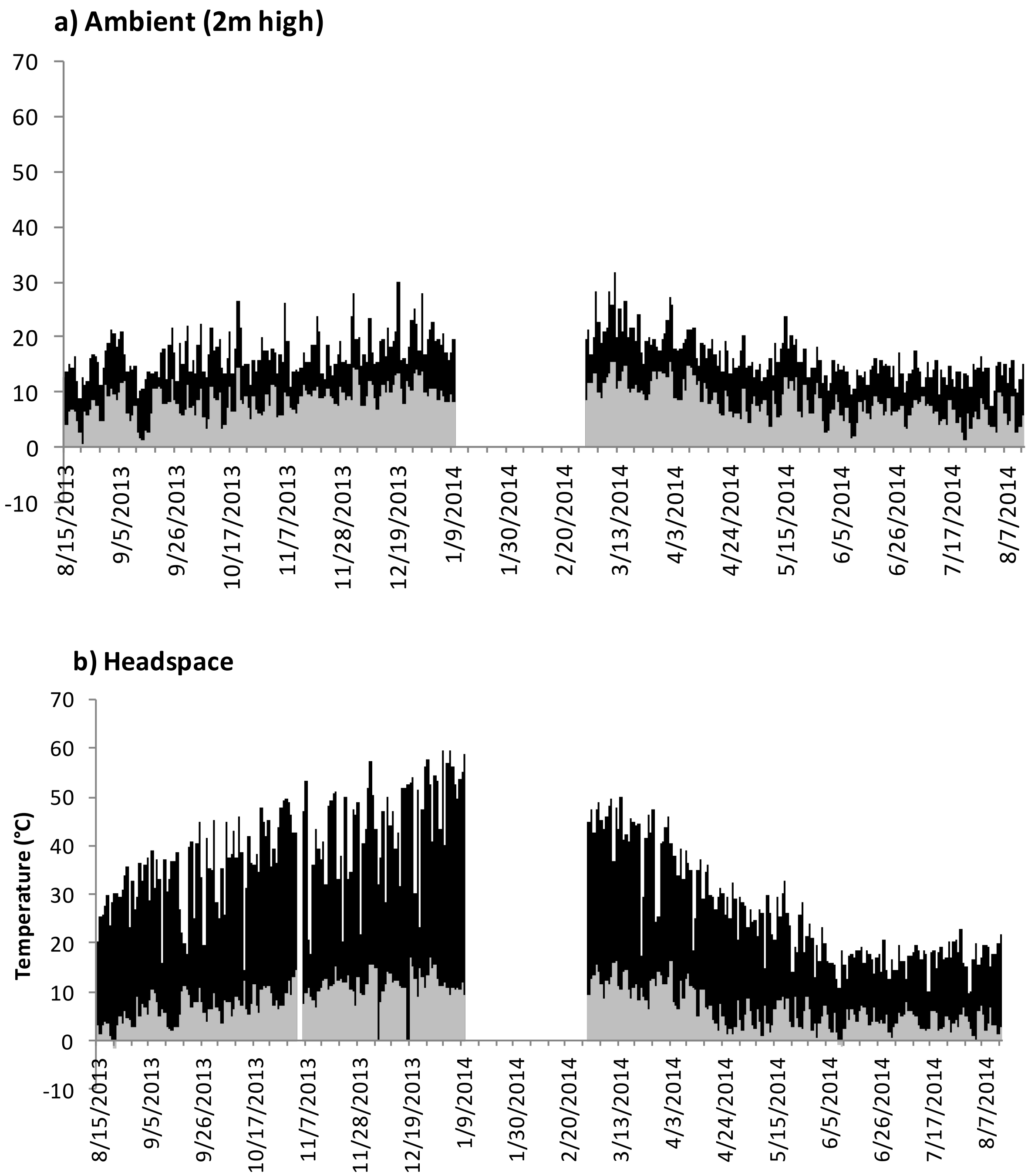
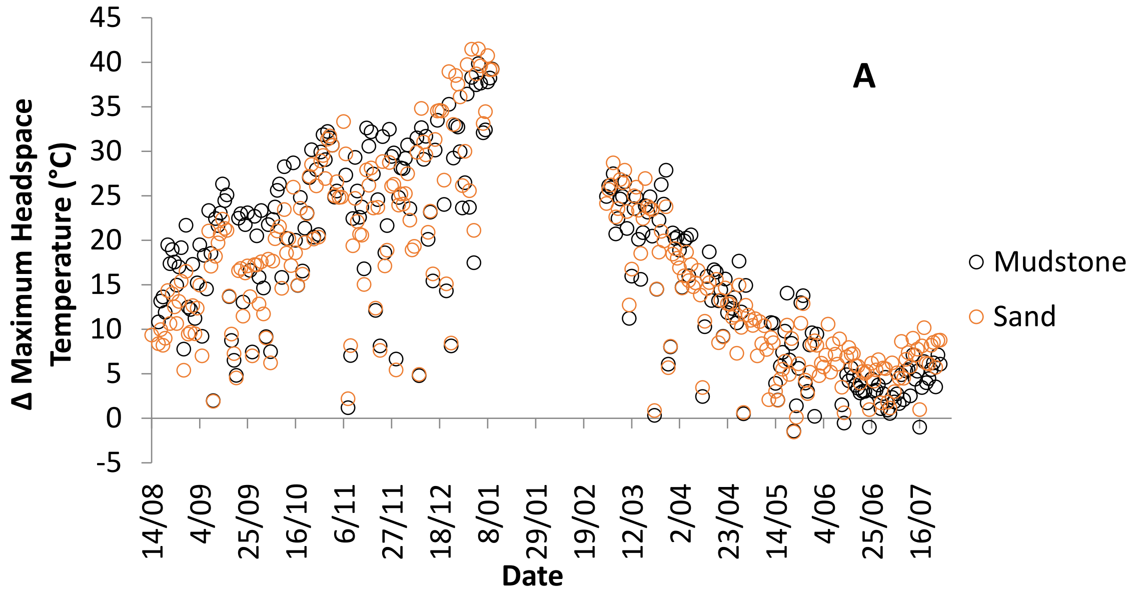


Figure 2.3 Daily minimum (light shade) and maximum (dark shade) temperatures under ambient (a) and headspace (b) conditions above the mudstone soil at Clifton. The observed data gap corresponds to the temporary disabling of the experiment when headspace temperatures approached the operating limits of the climate sensors.



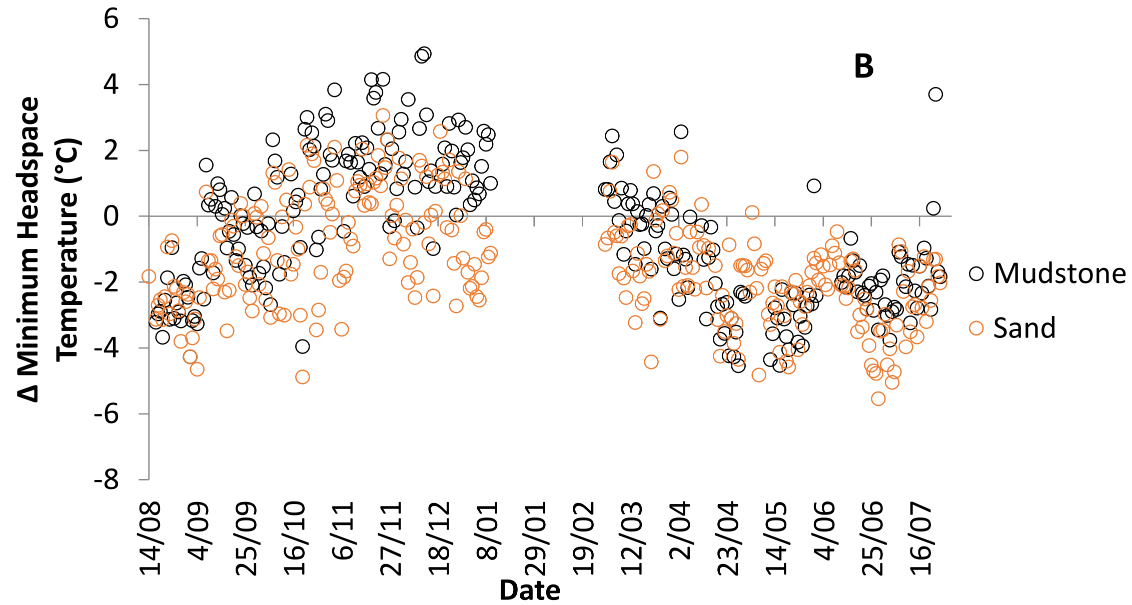
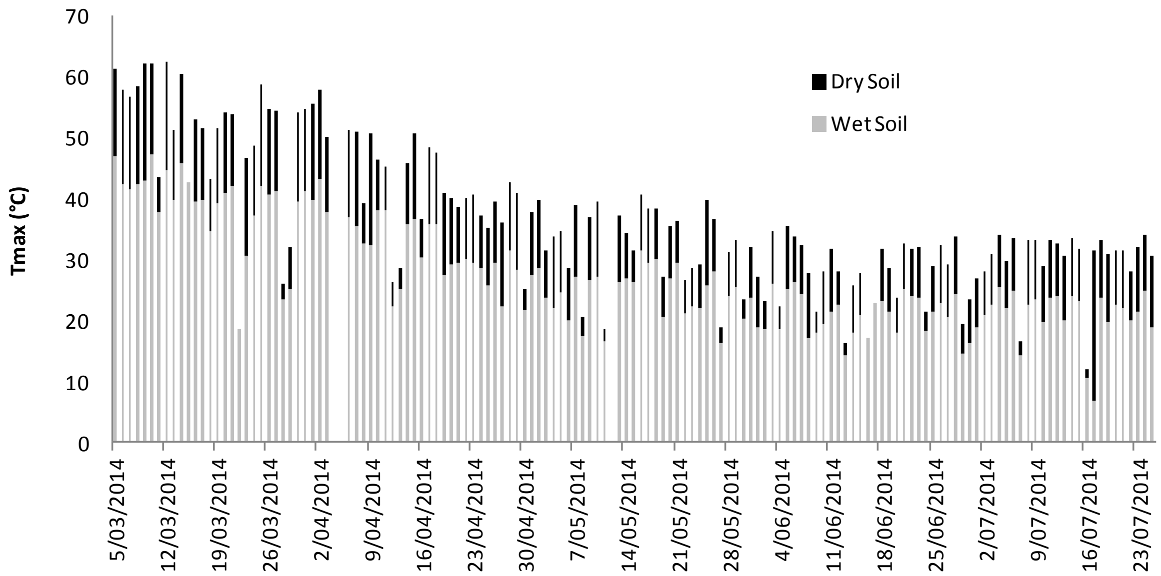


Figure 2.4 Difference between headspace and ambient (ground level) daily maximum (a) and minimum (b) temperatures for the sand and mudstone treatment at Clifton. The observed data/model gap corresponds to the temporary disabling of the trial when headspace temperatures approached/exceeded the operating limits of the climate sensors.

2.4.2 Soil Moisture

Maximum daily temperatures within the enclosed headspace varied with soil moisture content. Maximum daily temperatures in the headspace were largest in the dry silt soil treatment, increasing by 15 °C at the end of summer and up to 10 °C in winter. Daily minimum temperatures in the dry treatment were also 2-3 °C lower in the dry silt than the wet soil treatment and frequently reached 0 °C when day lengths were shorter during May and June at Clifton (Figure 2.5).



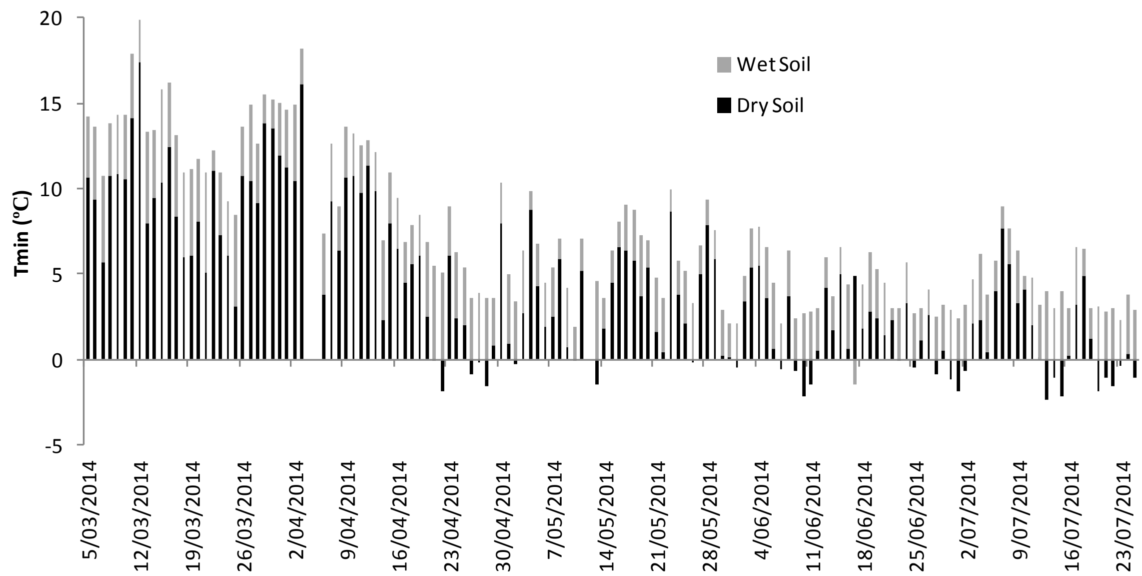


Figure 2.5 Daily maximum (A) and minimum (B) temperatures for 'dry' soil and 'wet' silt soil treatments (silt, Cambridge).

2.4.3 Headspace Atmospheric Composition

Following installation of the film, headspace [CO_2] rapidly rose above ambient atmospheric levels (~0.04 %), eventually oscillating around a plateau concentration where daily CO_2 inputs from soil respiration were balanced by 'leakage' from around the film to the atmosphere and losses from soil/plant sink processes (i.e. photosynthesis from emerging weeds, soil microbial uptake). The trajectory over time varied across the treatments (Figure 2.6), likely in response to differences in soil chemical and physical properties influencing rates of CO_2 sink and source processes (i.e. organic matter, C:N ratio, soil temperature). Small diurnal fluctuations are apparent with peak levels reached during the night and minimum levels at about midday, reflecting changes in the relative extents of CO_2 source/sink/loss processes throughout the day. The highest atmospheric [CO_2] level of ~4 % was approximately 100 times greater than ambient atmospheric [CO_2] concentrations (~ 0.04 %). The large magnitude of diurnal CO_2 fluctuations reflected the confined volume of headspace atmosphere. The highest CO_2 concentrations occurred in the mudstone (Soil 3; Cambridge) and silt (Soil 2; Clifton) treatments (Figure 2.7). The lowest concentrations of headspace CO_2 occurred for the sand treatment at Clifton, which is presumably attributable to the negligible levels of organic matter. However, similar low levels were also evident for the clay treatment at Cambridge, which had the highest levels of soil organic matter (Table 2.1). Clearly other soil physical and chemical properties are influencing microbial activity in this soil (Adu and Oades, 1978; Elliot 1986).

Temperature and solar radiation intensity were shown to have complex interactions with rates of CO_2 emission due to concomitant effects on [CO_2] uptake/emission (Figure 2.8). These effects include:

- positive [CO_2] uptake during periods of low temperature and high solar radiation intensity,
- neutral [CO_2] uptake/emission during periods of high temperature and high solar radiation intensity,
- negative [CO_2] uptake (CO_2 emission) during periods of low temperature and low/no solar radiation intensity,
- extremely negative [CO_2] uptake (CO_2 emission) during periods of high temperature and low/no solar radiation intensity.

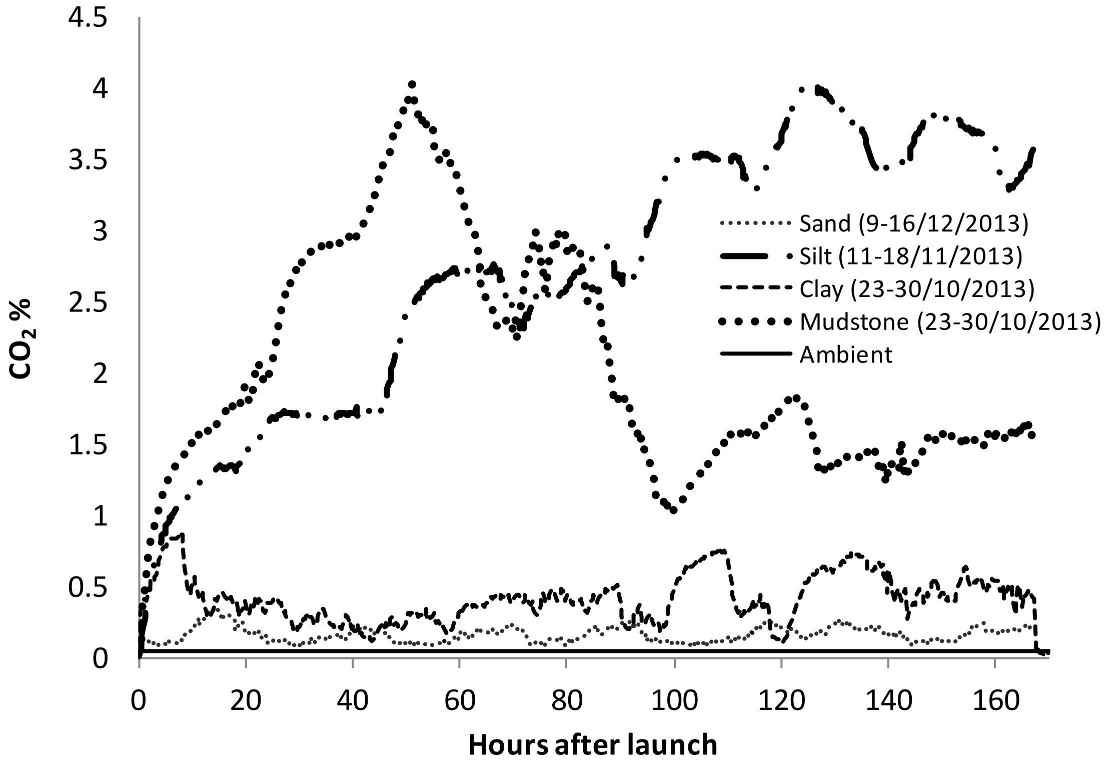


Figure 2.6 Headspace atmospheric carbon dioxide concentration trends over seven-day sample periods without plant growth.

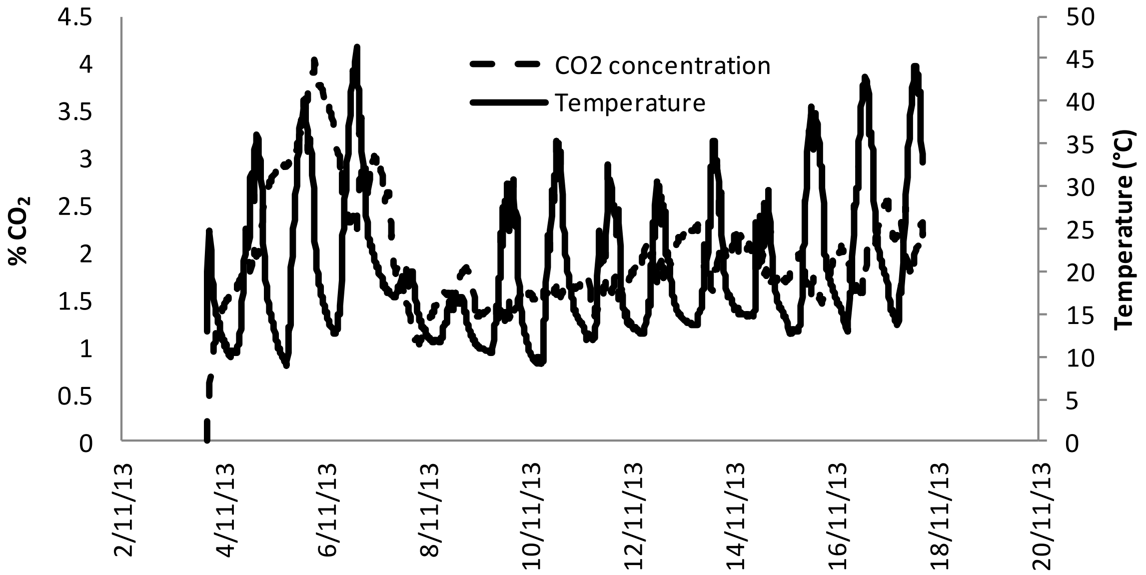


Figure 2.7 Headspace carbon dioxide concentration and headspace temperature for the mudstone treatment at Clifton when plants were growing beneath the film (November 2013)

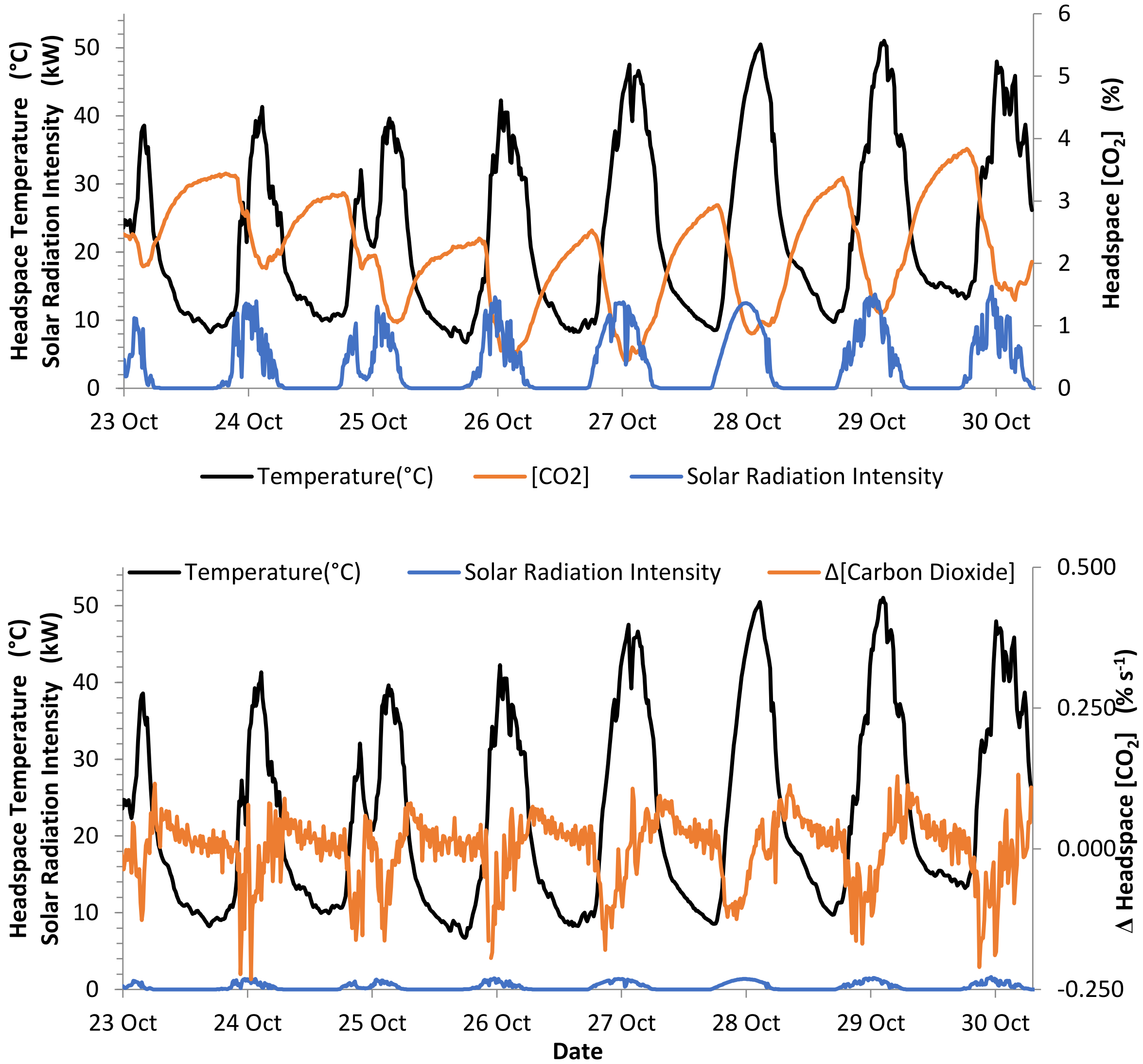


Figure 2.8 Gaseous concentration (A) and flux (B) of carbon dioxide within the enclosed headspace in response to changes in solar radiation intensity and headspace temperature on the mudstone soil treatment when plants were growing beneath the film at Clifton (October 2013).

Headspace relative humidity reached saturated concentrations throughout most of each day, regardless of season. Relative humidity was observed to decrease from saturation in response to increases in temperature during prolonged heating events (Figure 2.9). Within the film-enclosed environment, daily minimum relative humidity levels during this period typically remained above levels observed in the control treatments, with minimum daily values up to 55% higher under film (Figure 2.10). These pronounced diurnal oscillations in relative humidity were strongly associated with changes to the vapour pressure saturation point (VPSP), which increases or decreases exponentially in response to temperature (Waggoner and Reifsnyder, 1968).

Evaporation of water to fill this additional vapour pressure capacity during diurnal heating periods was significantly slower than concomitant increases in the vapour pressure saturation point, resulting in the formation of large vapour pressure deficits (VPD) and decreasing relative humidity levels (Waggoner and Reifsnyder, 1968). Maximum VPD under film in the wet soil treatments was as low as 0.5 kPa during winter months, increasing to 14.2 kPa at Cambridge and 15.1 kPa at Clifton during summer. By contrast, maximum daily VPD varied seasonally between 0.5 and 2.5 kPa within non-enclosed control treatments, with only eight days exceeding 2.5kPa. From this it can be concluded that atmospheric conditions within the film-enclosed headspace can become more desiccating during the daily heating period than plants normally experience during the driest conditions of summer. Overnight decreases in headspace temperature and VPSP were subsequently demonstrated to eliminate this diurnal VPD flux, causing relative humidity under film to return to 100% in all soil types and excess water vapour to form condensation.

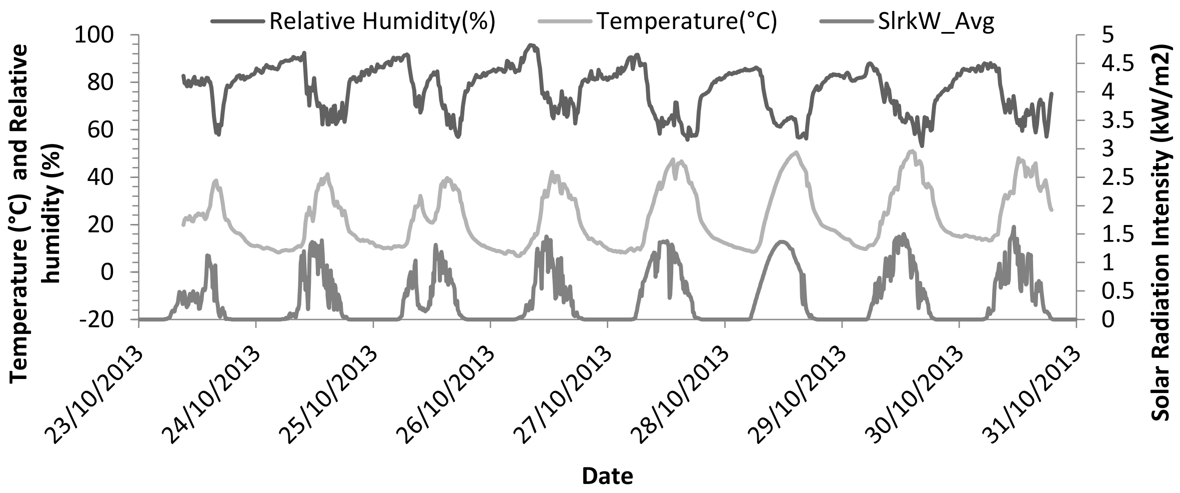


Figure 2.9 Diurnal fluctuations in headspace relative humidity (%), temperature (°C) and solar radiation intensity for the mudstone soil at Cambridge.

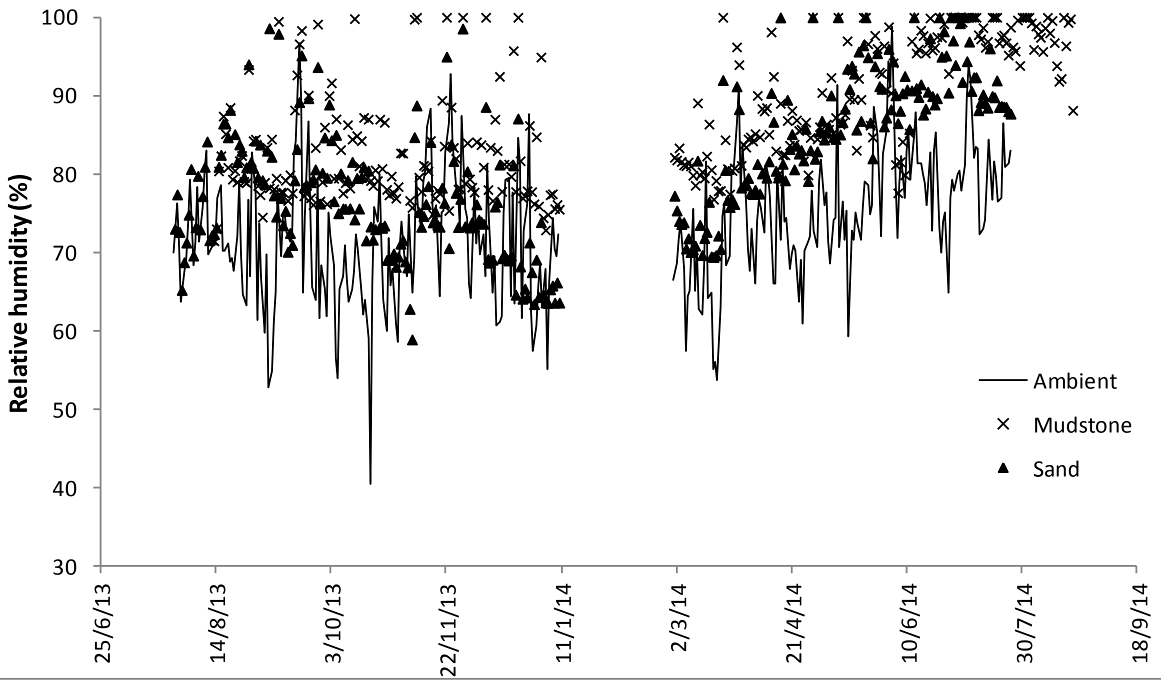


Figure 2.10 Average daily headspace relative humidity for the ambient, wet mudstone and wet sand treatments at Clifton Beach. The observed data/model gap corresponds to the temporary disabling of the trial when headspace temperatures approached/exceeded the operating limits of the climate sensors.

2.4.4 Solar Radiation Exposure Across Sites

Daily exposure to incident solar radiation varied at each site throughout the monitoring period. These variations were was associated with seasonal changes in maximum daily solar radiation intensity, day length and the duration of intermittent cloud cover. Solar radiation exposure was lowest during winter months, during which maximum daily solar radiation intensity was limited to 0.5 kW or less (Figure 2.11) and day lengths were frequently less than 10 hours in duration. Conversely, solar radiation exposure was greatest during summer when day length reached a maximum of 15 hours and maximum daily solar radiation intensity frequently exceeded 1.3 kW.

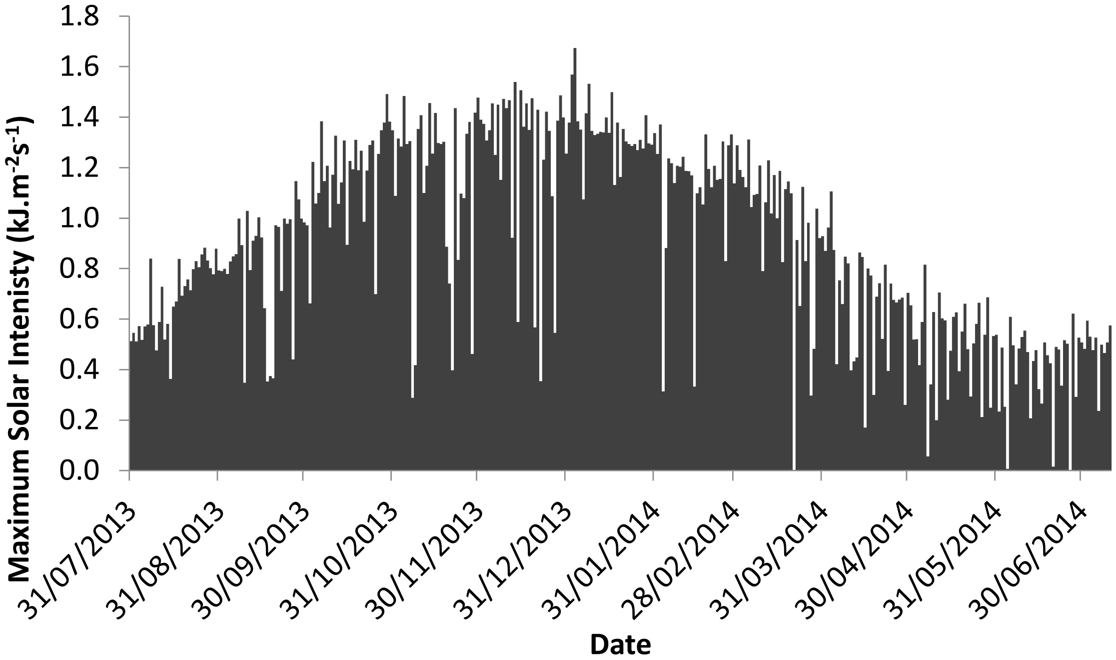


Figure 2.11 Example of seasonal changes in maximum daily solar radiation intensity at Cambridge.

2.4.5 Solar Radiation Transmission

Daily solar radiation was able to be transmitted through the film with 92% efficiency prior to the film being was installed under field conditions (Figure 2.12). In contrast, instantaneous solar radiation transmission rates were observed to be significantly lower when installed under field conditions due to soil moisture emissions and condensation effects. Rates of solar radiation transmission efficiency through the film varied between 68 % efficient in the sand treatment (y = 0.6819x; R^2 = 0.9582) and 48 % efficient in the mudstone treatment (y = 0.4816x; R^2 = 0.9484). Within each soil treatment, radiation transmission demonstrated strong linearity and constancy (Figure 2.13, Figure 2.14). No relationship was observed between solar radiation transmission efficiency through the polymer row covers in response to relative humidity, temperature or vapour pressure deficits within the confined headspace environment (not shown), indicating minimal seasonal variance in solar radiation transmission efficiency.

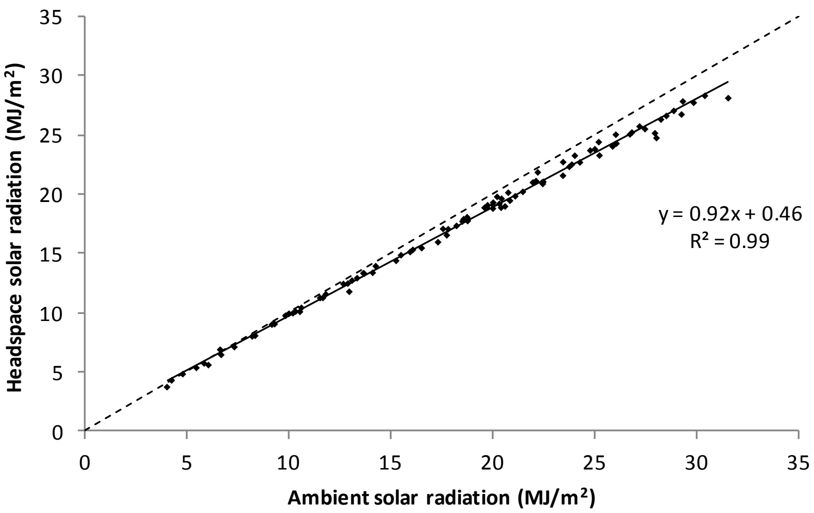


Figure 2.12 Relationship between headspace and ambient total daily solar radiation before film installation. The dashed line is the 1:1 relationship.

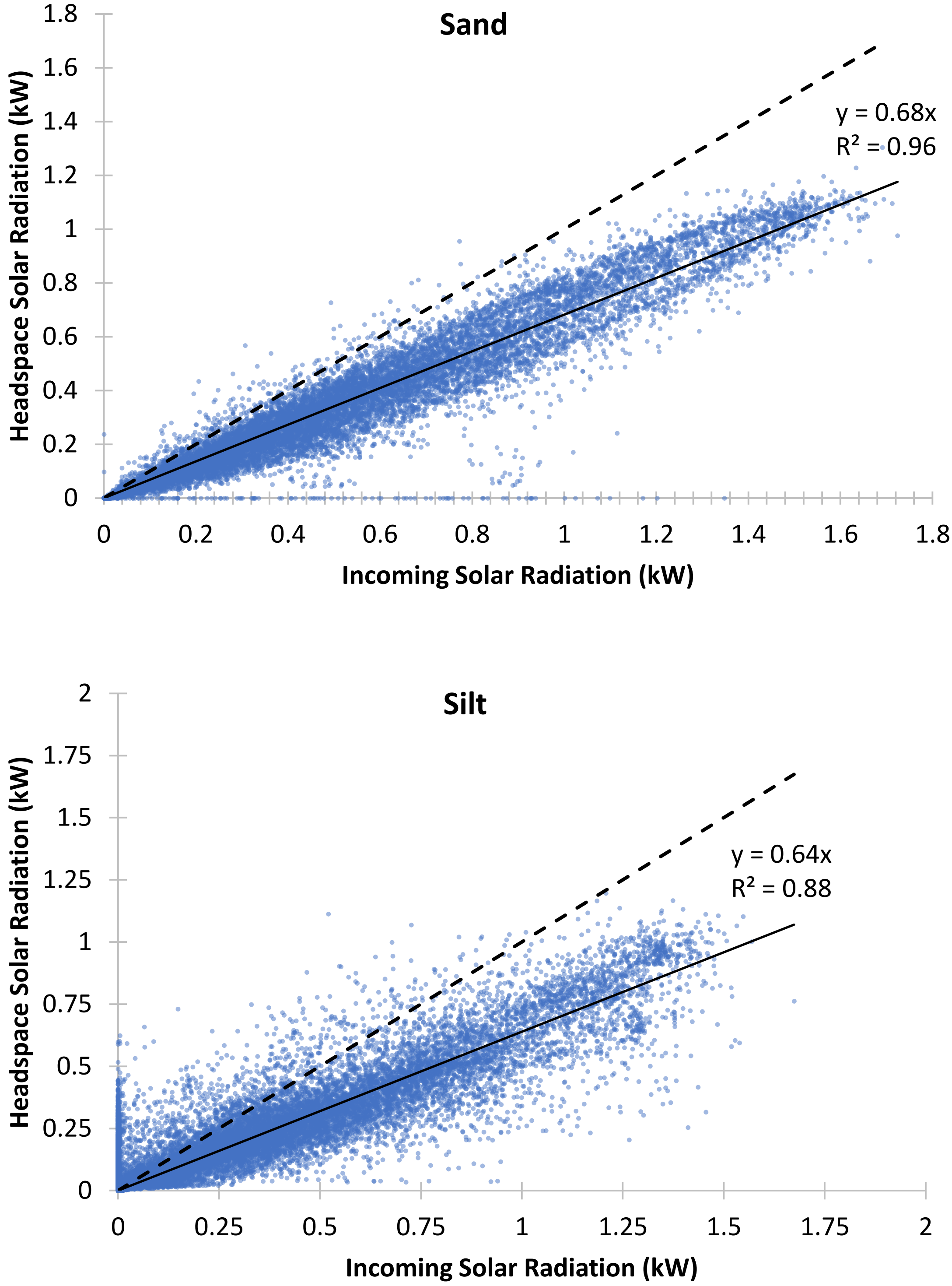


Figure 2.13 *In situ* instantaneous transmission of incoming solar radiation through the film layer when installed above sand and silt soils at Clifton.

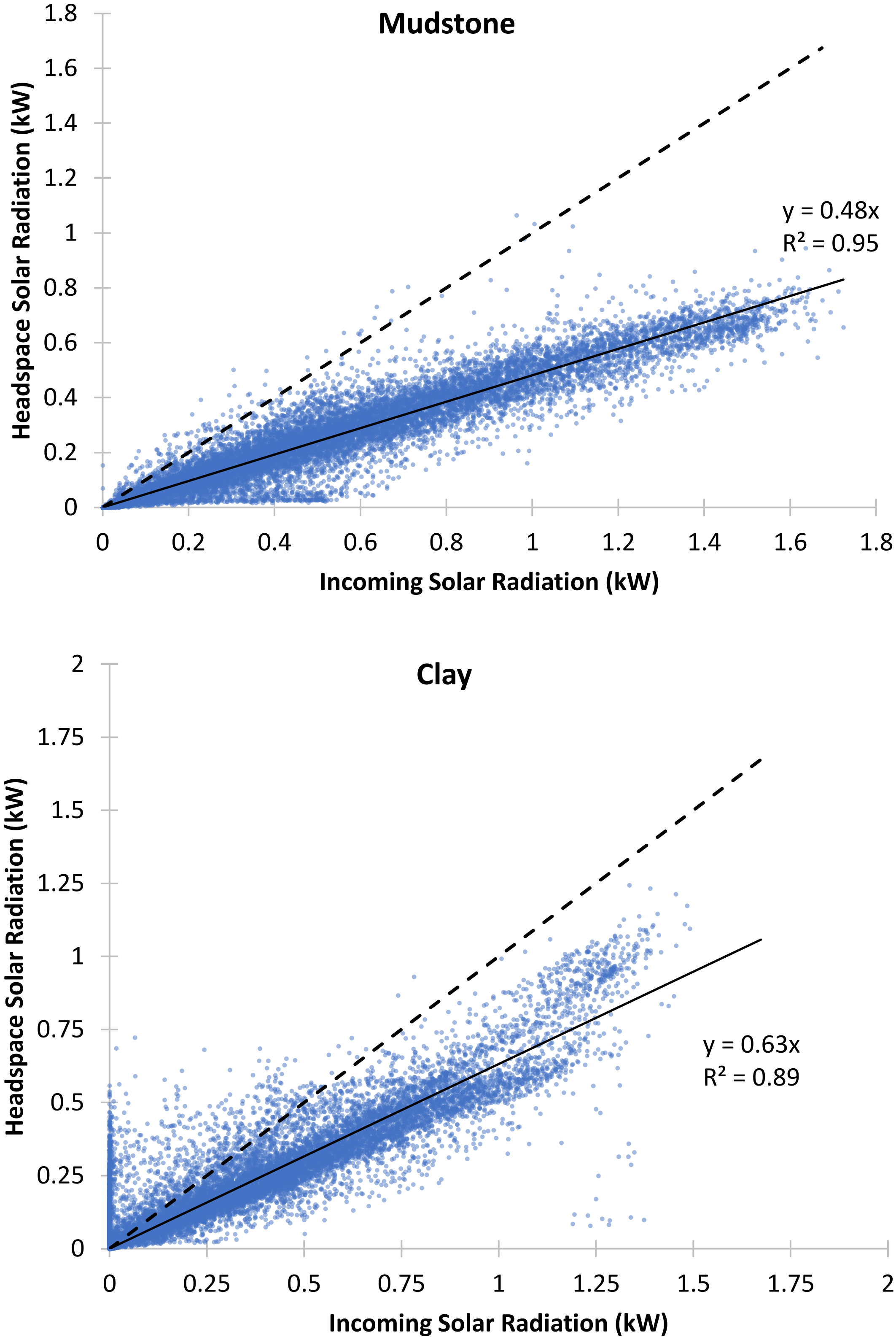


Figure 2.14 *In situ* instantaneous transmission of incoming solar radiation through the film layer when installed above mudstone and clay soils at Cambridge.

2.5 Discussion

Use of polymer row covers in agricultural systems for environmental seasonal climate modification is dependent on the technology's capacity to create conditions suitable for early plant growth and development under a variety of seasonal and environmental temperature and solar radiation conditions. Due to its comparatively high-latitude location, southern Tasmania is one of the most seasonally variable regions of Australia, providing a wide range of day length (i.e. 9 to 15.3 hours) and ambient climatic conditions with which to collate field data to develop headspace climate model relationships for different soil treatments.

Defining the operational limit for film use to avoid crop growth suppression or death is a critical first step in determining the suitability of film for a given location and application. The maximum sustained temperature that plants can survive is confined to a relatively narrow range of 40 to 45 °C, beyond which the denaturation of key growth enzymes will lead to plant death (Corkrey *et al.*, 2014). The actual threshold maximum temperature for a given species varies in response to the presence and efficacy of various thermo-tolerance mechanisms (Senioniti *et al.*, 1986). During the experimental period, headspace temperatures rose above 45 °C from early October 2013 to early April 2014. These headspace temperatures conditions created through film use are not suitable to plant growth during the summer months but are being increasingly adopted for use in soil solarisation and weed/pathogen pest control.

An important prerequisite for accurately predicting headspace temperature fluctuations under film is the accurate estimation of solar radiation transmission and absorbance. On its own, film was shown to attenuate only 8% of incident solar radiation before installation, but caused a much larger proportion of incident solar radiation to be attenuated under normal field use. The presence of water drops greatly reduced solar radiation transmission through the film layer, creating a visible "whitening" of the film surface that increased radiation reflectance and scattering, reducing instantaneous transmission rates to 48-68% (Pollet *et al.*, 2015, Pieterson *et al.*, 1997). Transmission rates of solar radiation through this complex film-water membrane was highly linear across all seasons despite pronounced diurnal and seasonal fluctuations in headspace temperature, relative humidity, vapour pressure deficit, and surface water content on the underside of the film membrane (Jaffrin and Mahklouf, 1990). As such, it can be inferred that the actual volume of water present on the underside of the film surface had minimal influence over instantaneous film transmission rates. In applications where solar radiation attenuation or condensation from macroscopic and microscopic droplets is likely to be problematic, condensation formation and radiation attenuation may be able to be significantly reduced through the use of commercially available polymer-additive blends that reduce droplet attenuation to approximately 3% of total incoming solar radiation (Pearson *et al.* 1995).

Soil water content has a strong influence on headspace temperature and relative humidity, with the 'dry' soil treatment having a diurnal temperature range up to 16 °C greater than the respective 'wet' soil treatment. These higher maximum and lower minimum temperatures need to be taken into consideration when determining the safe operational limits of film for a given crop type and location. In particular, dry soils pose a much greater cold-stress risk when film is used during the cooler times of the year for faster/earlier crop establishment (Robertson *et al.*, 1999). Hence, variation of soil moisture under film through either pre-placement irrigation or via waiting for soil moisture to reach specific levels via rainfall prior to film placement might be a key part of effective use of film in crop production.

Soil type also demonstrated an influence on solar radiation transmission and attenuation rates, with the soils presented here attenuating between 32% and 52% of incident solar radiation exposure beneath the polymer row covers. These differences in solar radiation transmission may reflect variations in surface roughness and porosity, textural heterogeneity, albedo, moisture content, bed structure and/or angle of inclination between the film surface and sun, although the precise mechanisms involved are uncertain at this point in time.

Film could be used to expand the duration of the growing season by enabling earlier sowing and faster establishment by increasing the soil temperature and substantially reducing frost risk. Crops grown beneath film would accumulate thermal time at a faster rate than crops growing under ambient conditions, enabling them to mature earlier with less chance of being exposed to drought or late-season frost damage (Lorenz and Maynard 1980). Through these types of changes, film use may enable the geographical expansion of production of crops such as maize to areas that are otherwise unsuited to production.

The recorded increases in daily maximum and minimum temperatures of up to 7 °C in early to mid-spring have the potential to transform the production of a range of cold-sensitive crops in Australia. For example, the establishment, growth, maturation and quality of maize and sweet corn are cold-limited and frost-sensitive. Production of these and similar crops is thus currently confined to the warmer months using short-season varieties that are able to mature within the narrow growing window. Despite best management practices, untimely frost events early or late in the season can adversely affect grain yield and quality (Pembleton and Rawnsley, 2012). Similarly, later planting dates in these cold- and frost-limited regions also delay the transition from vegetative to reproductive growth to early summer, resulting in heat- and drought-sensitive reproductive stages (e.g. silking, anthesis and early zygote formation) occurring during the hottest temperatures of summer (Bollero *et al.*, 1996; Birch *et al.*, 1997). Management of these stresses in Australia requires full or targeted irrigation, and failure to do so in an effective manner greatly reduces pollen viability, zygote conception and survival, and subsequent grain yield and density (Banabás *et al.*, 2008).

The accumulation of high levels of CO_2 under film has been noted in other studies (Rubin and Benjamin, 1984; Sheldrake 1963). There is a growing body of evidence that increasing [CO_2] may influence plant sensitivities to both high and low temperatures. In *Azolla sp.* and many C_3 species, CO_2 concentrations of 700 ppm have been found to enhance photosynthesis rates under supra-optimal temperatures, providing heat relief to plants under conditions that would otherwise inhibit growth (Idso *et al.* 1989; Wang *et al.*, 2008). Conversely, C_4 and CAM species growing in enriched CO_2 environments demonstrate greater sensitivities to heat stress when grown under enriched [CO_2], indicating interactions between CO_2 and heat tolerance mechanisms between these groups (Keeley and Rundel, 2003). This complexity of plant physiological responses under film to carbon dioxide concentrations is further complicated by higher atmospheric moisture contents and varying vapour saturation points. These physiological responses are the subject of discussion in subsequent chapters.

2.6 Conclusion

This chapter reports on a year-long study into the effects of film on the headspace across a range of soil types. The film fundamentally altered the growing environment via: (a) heat entrapment due to the differential permeability of film to terrestrial (long wave) and solar (short wave) radiation, which raised the daily maximum temperatures to a peak of ~60 °C and daily minimum temperatures up to 30 °C above ambient levels in summer; (b) film entrapment of CO_2, which led to increases in atmospheric [CO_2] up to 100 times ambient levels; (c) rapid temperature-induced changes in relative humidity, vapour saturation points and vapour pressure deficits; and (d) attenuation of incident solar radiation by the film itself (~8%) and condensation (up to 26%) formed on the underside surface of the film. The magnitudes of these responses were all sensitive to soil type. The following chapter will use this information to construct a biophysical model of headspace microclimate under film.

Chapter 3: Biophysical Modelling of Headspace Microclimate

3.1 Abstract

Farmers' decisions relating to the adoption and use of new technologies like film are complex and multifaceted. Defining the 'safe' operational limit for film use is a critical first step in determining the suitability of film for a given location and application, so as to avoid crop growth suppression or death. One means of exploring and addressing these complex questions is by using agricultural production simulators like APSIM.

In this chapter, film climate models were developed to predict maximum and minimum headspace temperatures under film from daily climate observations. These models were imported into APSIM to create a biophysical model of headspace microclimate. APSIM was then used to develop a model of daily temperature and solar radiation at four Tasmanian agricultural sites based on SILO meteorological information. Heat stress thresholds for temperate and tropical cereals were used to estimate daily heat stress exposure for temperate and tropical crops respectively using the temperature response curves in APSIM's 'Wheat' and 'Maize' modules. Temperate cereals growing within film-enclosed environments had a low (< 10 %) probability of experiencing heat stress between late May and mid-July, but were highly likely to be affected by heat stress if film was used outside of this period. Film use created conditions suitable for the establishment and production of tropical cereals between mid-April and early September. Film use outside of this period could cause causing crops beneath the film to experience heat stress under some ambient conditions. Ultimately, determining the optimal duration of film use is dependent on individual film users' attitude toward risk.

3.2 Introduction

Use of film has been proposed as a means of improving crop production in Tasmania. Farmers' decisions relating to the adoption and use of new technologies like film are complex and multifaceted. As noted in the preceding chapter, film can potentially be used to modify environmental conditions by increasing daily temperature fluxes and soil moisture retention, and by reducing solar radiation intensity. For agricultural producers, the introduction of film for seasonal climate manipulation creates new options for a wide range of management decisions including crop and cultivar selection, sowing time, harvesting arrangements, fertiliser use, and weed management (Kasirajan and Ngouajio, 2012). Spatial heterogeniety in soil characteristics, seasonal climate variability, and longer-term trends in climate change add further variables to this decision making, increasing the complexity of developing optimal agronomic management decisions in a film-enclosed agricultural production system (Lisson *et al.*, 2010).

Defining the safe operational limits for film use is a critical first step in determining the suitability of film for a given location and application (Wang *et al.*, 2004; Zhou *et al.*, 2009; Lisson *et al.*, 2016). Assessing the likely safety of film use in different agricultural regions and management systems requires the ability to predict the daily minimum and maximum headspace temperatures from available ambient climate data (Hammer *et al.*, 1982; Keating and Wafula, 1992; Carberry *et al.*, 2009; Dilla *et al.*, 2018; Soufizadeh *et al.*, 2018).

Very few empirical models have been developed to predict air and soil characteristics beneath film. To date, previous modelling of the sub-film environments has instead focused on prediction of soil temperature profiles for soil solarisation using clear and black mulch films (Mahrer 1979; Wu *et al.* 1996). These soil temperature models require historical, short-interval ambient climate data and information about soil chemical and physical properties which is often not available, as well as extensive information regarding film optical properties that is commercially sensitive in nature and also not available to potential film users. For this reason, such comprehensive models are unlikely to be useful in decision-support applications due to the lack of available information.

One means of exploring and addressing these complex questions is by using agricultural production simulators like APSIM. APSIM is a mechanistic crop production simulator that combines plant development and yield models with site-specific meteorological, soil and agronomic management (Keating *et al.*, 2003). APSIM was developed and released in 1990's (Keating *et al.*, 2004), and experienced a period during the 1990's and early 2000's where it was heavily An early application of this software was assessment of the suitability of regions for new crop species, including maize (Hammer *et al.*, 1993; Carberry *et al.*, 1993a; Carberry *et al.*, 1993b; Meinke *et al.*, 1993; Robertson *et al.*, 1993; Birch *et al.*, 1998). Since this period, APSIM continues to gain new capabilities (Dilla *et al.*, 2018; Soufizadeh *et al.*, 2018) and continues to be applied as an import tool in new regions (Kisaka *et al.*, 2016; Sun *et al.*, 2016; Tong *et al.*, 2016). In Australia, APSIM is a widely used software tool to simulate crop ontogeny, productivity and environmental interactions in broad-acre applications (Wang *et al.*, 2018; Seyoum *et al.*, 2017; Myoung *et al.*, 2015; Soufizdeh *et al.*, 2018; Dilla *et al.*, 2018).

APSIM and other agricultural production simulators can only be accurately applied in situations where appropriate biophysical models are available (Keating *et al.*, 2003). To date, little attention has been devoted towards the development of biophysical models to support microclimate and crop performance modelling under film. As discussed in Chapter 2, installation of the clear film material can alter air temperatures, solar radiation attenuation and atmospheric composition within the enclosed environment and no biophysical models have been developed to estimate these effects. Presented in this chapter are models of daily headspace temperature and solar radiation developed from intensive monitoring under diverse field conditions, which are able to be incorporated into the broader APSIM modelling framework. APSIM was then used to explore seasonal temperature and frost risk for different Tasmanian locations, and the implications for film use in temperate and tropical cereal production systems are discussed.

3.3 Materials and Methods

3.3.1 Headspace Data Collection

Headspace climate data used for model development was sourced from the dataset collected in Chapter 2. This data was collected from two sites near Clifton Beach (42.59°S, 147.31°E) and Cambridge (42.79°S, 147.42°E) in southeast Tasmania. Data recording for this trial was carried out over a 12 month period (i.e. August 2013 to August 2014) to capture information about a wide range of ambient climate and related conditions (e.g. sun angle, day length) necessary for model development.

3.3.2 Headspace Model Development

3.3.2.1 Maximum and Minimum Daily Solar Radiation and Air Temperatures

The development and testing of air temperature and solar radiation models was performed using PROC GLMSELECT and PROC GLM in SAS version 9.3 Software (SAS 2012). To select predictive variables for each outcome, two thirds of the data was randomly chosen as a training set and the remaining one third as a testing set. The predictors included: T_{max}, maximum daily ambient temperature; T_{min}, minimum daily ambient temperature; R, solar radiation; and D, day length as a proportion of 24 hours (e.g. 6 hours corresponded to 0.25). A one-day lag; e.g. Lag(T_{max}) was also included. The training set was used to fit the model.

The testing set was used to assess model fit and to select terms to drop and add to the model using a stepwise procedure in which the average square validation error was used to identify useful terms. Terms were added or dropped using the significance level of 0.05. Only ambient (i.e. not headspace variables) predictor variables were considered for the current and previous days. Interaction and power terms up to the third power were included in the analysis. Separate analyses were conducted for each of the four soils from Chapter 2, as well as the combined data from all wet-soil datasets.

A second group of simple models, excluding the power and interaction terms, was then generated. Typically, the simple models closely matched the more complex models across all statistical metrics (<1% difference, data not shown) and hence only the simple models are presented in this paper. Examination of residual plots indicated that no data transformation was required. Model performance was measured using the adjusted-R^2 and Nash-Sutcliffe (E) statistic (Nash and Sutcliffe 1970). For the latter metric, a perfect prediction results in E = 1, a model that predicted no better than the mean results in E = 0, and a model with poorer prediction than the mean results in E < 0. Other metrics included the mean absolute deviation and the proportion of points in the test dataset within the 95% prediction interval.

3.3.2.2 Diurnal Temperature Distribution

APSIM interpolates daily temperature changes by interpolating daily heat exposure into eight three-hourly time periods (hereafter referred to as “time-points”), which are used for estimating crop heat exposure and development. These time-points are non-temporal, and do not correspond to any particular period or time throughout the day. Instead, each time-point represents the average of 12.5 % of a sorted list of temperature observations measured throughout a 24-hour period. In this manner, time-point 1 represents the average of the 12.5 % of daily observations with the greatest level of heat exposure, whilst time-point 8 represents the average of the 12.5 % of daily observations with the lowest level of heat exposure.

To compare observations against this model, distributions of normalised 10-minute temperature observations throughout June (the shortest month) and December (the longest month) were visually assessed to determine seasonal homogeneity. Daily 10-minute temperature observations for each day were ranked by temperature, then adjusted for the daily minimum temperature and divided by the differential in maximum and minimum daily temperatures (T_{diff}) (i.e. $T_{max} – T_{min}$) to create a normalised temperature index. These observations were compared with the normalised interpolated temperature outputs currently utilised by APSIM to determine model "goodness of fit".

Daily temperature observations were ranked by percentile and subdivided into eight equal subsets. Temperatures in each subset were averaged using median values to minimise heat-loss effects associated from short-term cloud cover. Stepwise linear regression using R Studio v0.99.903 (R Studio, Boston, MA, USA) was then performed to predict daily median values for each subset using the daily time step in APSIM. To select predictive variables, 20% of the data was randomly selected as a training set and the remaining 80% as a testing set. The final set of predictors consisted of T_{min}, minimum daily ambient temperature, and $T_{diff,}$ maximum daily temperature differential; and interpolated time-point. The training set was used to fit the model against the larger dataset, with model outputs compared against the interpolated temperature outputs of the model currently utilised by APSIM.

3.3.3 Model Component Validation

One third of the data collected over the 12-month period was used to independently test the models derived from the remaining two thirds of the dataset. These attributes maximise the robustness of the model relationships and should enable their transferability to a wide range of environments.

3.3.4 Integration into APSIM

Film climate models developed in Chapter 3.2.2.1 were imported into APSIM using the *Prenewmet* rule in the Climate Control manager module to estimate daily T_{max}, T_{min} and solar radiation exposure within the enclosed headspace (see Appendix 1). Temperature distribution models developed in Chapter 3.4.2.2 were imported into APSIM using an *Empty Manager* rule in the manager module to calculate three-hourly estimates of headspace temperature.

Three-hourly headspace temperatures were used to estimate potential for thermal time accumulation for temperate and tropical cereals. Thermal time for temperate and tropical crops was calculated using cardinal values for wheat and maize respectively (Table 3.1). Linear interpolation was used to calculate thermal time values for headspace temperatures between each cardinal value. Temperatures outside these cardinal values were assigned a value of 0. Daily thermal time estimates (in degree days) were subsequently calculated by taking the mean of each three-hourly thermal time value. Inhibition of crop development caused by heat stress was estimated by calculating the degree-days lost due to supra-optimal temperatures. Inhibition of development caused by cold stress was estimated by calculating the degree-days lost due to sub-optimal temperatures.

Table 3.1 Cardinal temperatures for thermal time accumulation in wheat (*Triticum aestivum* L.) and maize (*Zea mays* L.) used by the APSIM model.

Headspace temperature	Maize thermal time	Headspace temperature	Wheat thermal time
(°C)	(°DD)	(°C)	(°DD)
0	0	0	0
18	10	26	26
26	18	34	0
24	26		
44	0		

Three-hourly headspace temperatures were also used to estimate the thermal effects upon daily radiation use efficiency (RUE) for temperate and tropical cereals using the approach of Monteith 1977. RUE was estimated using the RUE cardinal values outlined in Table 3.2, with linear interpolation was used to estimate median RUE for headspace temperatures between each cardinal value. Temperatures outside these cardinal values were assigned a value of 0. Estimates of daily RUE was subsequently calculated by taking the mean of each three-hourly RUE estimate.

Table 3.2 Cardinal temperatures for radiation use efficiency in wheat (*Triticum aestivum* L.) and maize (*Zea mays* L.) used by the APSIM model.

Headspace Temperature	Maize RUE	Headspace Temperature	Wheat RUE
(°C)	(%)	(°C)	(%)
8	0	0	0
15	1	10	1
35	1	25	1
50	0	35	0

3.3.5 APSIM Crop Model Development

Following module development, APSIM was used to develop a model of daily temperature and solar radiation at four Tasmanian agricultural sites (Table 3.3). For this simulation, SILO meteorological information for each site was imported into APSIM. These simulations were run over a 127-year period (1 January 1889 to 31 December 2015) to maximise seasonal variability.

Ambient frost-risk days were defined as any day where the minimum ambient air temperature at 1.2 metres was less than 2.0 °C. Potential frost events were defined to preferentially occur on the outside of the headspace due to the insulating properties of the film and the increased humidity and latent heat capacity in the film-enclosed headspace (see Chapter 2.4.4). Daily temperature, solar radiation, and frost-risk outputs from this simulation were analysed against observed conditions using R Studio.

Soil water, nitrogen and phosphorus parameters used for these simulations measured and recorded by researchers at the Tasmanian Institute of Agriculture for the Elliott area, and have been incorporated and published in several peer-reviewed studies, including Rawnsley and Pembleton (2012) (Table 3.4). These parameters were reset at the start of each month to minimise any cumulative model effects from soil water redistribution, and irrigation equal to soil moisture evaporation was simulated to return any recondensed water beneath the film. Within the APSIM model, the effects of soil bulk-density upon crop biomass and development are negligible in simulations where water is non-limiting for plant growth.

Table 3.3 Location details for four agricultural sites in Tasmania

Site		Bothwell	Campbell Town	Devonport	Elliott
Latitude	(°S)	42.4	41.9	41.2	41.1
Longitude	(°E)	147.0	147.5	146.4	145.8
Elevation	(m)	352	209	10	155

Table 3.4 Key physical, nutrient and soil water properties of the soil used for all sites

Depth	Bulk Density	LL15	DUL	ρH	[OC]	$[NO_3^-]$	$[NH_4^+]$
	(g cm^{-3})	(g cm^{-3})	(g cm^{-3})	(1 : 5 water)	(%)	(ppm)	(ppm)
0-20	0.8	0.21	0.34	6.9	0.7	1.0	10.0
20-36	0.8	0.21	0.33	6.5	0.7	2.0	6.0
36-48	1.0	0.3	0.42	5.5	0.4	1.0	0.3
48-80	1.0	0.31	0.43	5.5	0.3	1.0	0.1
80-110	1.1	0.36	0.49	5.5	0.2	0.0	0.0

3.4 Results

3.4.1 Solar Radiation

Linear regressions of daily solar radiation exposure within the film-enclosed headspace indicated that rates of radiation transmission were greatest in the silt-rich loam soil (y = 0.81x + 1.56; R^2 = 0.94) and lowest in the mudstone soil (y = 0.67x – 0.09; R^2 = 0.97) (Figure 3.1). Variations in total daily solar radiation exposure under the film were predicted using simple models based on day length and ambient radiation across each of the four soil treatments in the headspace dataset (Figure 3.1; Figure 3.2). E values for each of these models ranged from 0.93 to 0.98, whilst a combined model had an E value of 0.91 (Table 3.5).

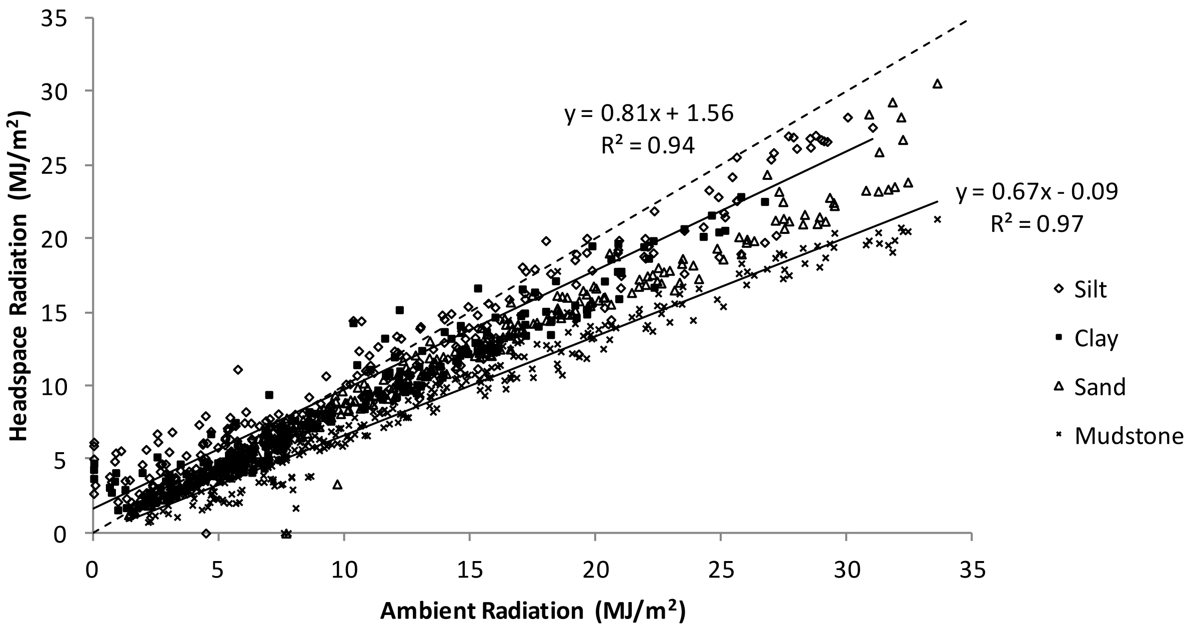


Figure 3.1 Relationship between headspace and ambient total daily solar radiation for the four soil treatments. Linear regressions are shown for the silt (minimum attenuation) and mudstone (maximum attenuation) treatments only. The dashed line is the 1:1 relationship.

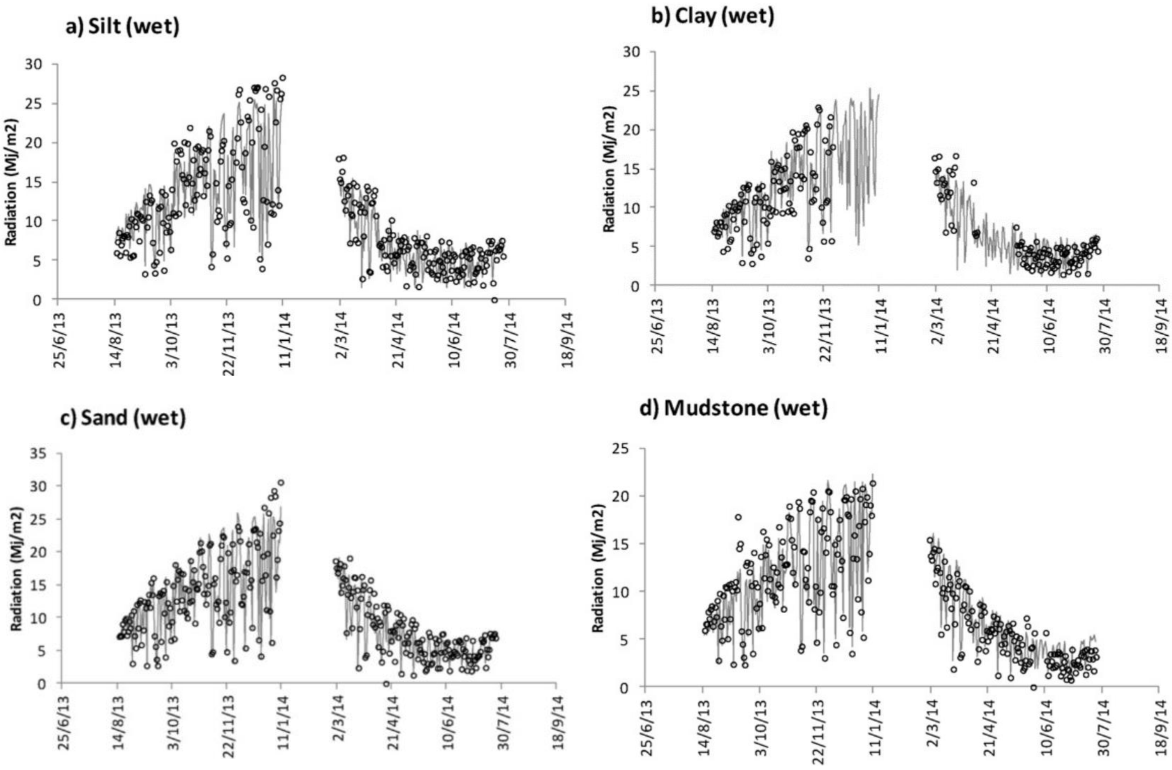


Figure 3.2 Observed (hollow points) and model (line) headspace radiation for each of the four soil treatments. See Table 3.5 for corresponding model equations and statistics. The observed data/model gap corresponds to the temporary disabling of the trial when headspace temperatures under the film approached/exceeded the operating limits of the climate sensors. The missing observed data for the clay treatment is due to bird damage.

Table 3.5 Model equations and performance statistics for daily headspace solar radiation exposure (MJ/m^2) for wet sand, silt, mudstone and clay soils described in Chapter 2.3.1. Collective 'all soil' regression models across all data are shown in bold text. All model coefficients are significant at the 0.01 level or lower. D = day length, R = ambient solar radiation. Lag ('X') refers to the previous day's value of the climate variable 'X'. The HS subscript refers to the headspace equivalent of the ambient climate variable.

Variable	Model	Adjusted R^2	Nash-Sutcliffe statistic E	Mean absolute deviation	Correct predictions within 95% CI
R_{HS} Wet clay	R_{HS} = 0.7431*R + 5.683*Lag(D) – 1.386	0.95	0.95	0.82	0.95
R_{HS} Wet silt	R_{HS} = 0.8160*R + 1.520	0.94	0.94	1.22	0.94
R_{HS} Wet sand	R_{HS} = 0.7978*R – 2.906*Lag(D) + 1.780	0.98	0.98	0.58	0.95
R_{HS} Wet mud	R_{HS} = 0.6332*R + 4.358*D – 1.747	0.97	0.97	0.68	0.97
R_{HS} Wet soils	**R_{HS} = 0.7034*R + 3.7529*Lag(D) – 0.4759**	**0.91**	**0.91**	**1.31**	**0.93**

3.4.2 Maximum and Minimum Daily Headspace Temperature

Simple models for accurately predicting maximum and minimum headspace temperatures under film from daily climate observations were derived for each wet soil treatment. Parameters included in these models included day length, ambient radiation and ambient maximum daily temperature variables (Table 3.6). Model structure and predictor variables varied with soil type, with E values ranging from 0.79 for wet silt to 0.94 for wet clay (Figure 3.4). Maximum daily temperature, ambient radiation, maximum ambient temperature and day-length predictors were conserved across all models. Ambient maximum daily temperatures from the previous day ($LagT_{max}$) were also found to be significant factors in wet clay and wet mudstone treatments, suggesting greater carryover of stored heat from the previous day.

The structure and predictor variable composition of models for minimum daily temperatures varied significantly with each soil treatment, with ambient minimum temperature the only predictor that appears in all models (Table 3.6). These models were less accurate than the maximum temperature models, with E values ranging from 0.79 for the mudstone soil to 0.9 for the clay soil. As expected, there was a carryover effect from the previous day's ambient radiation and maximum temperature.

Soil moisture content was observed to have a strong impact on maximum headspace temperatures under the film, with daytime maximum temperatures consistently higher for dry soils when compared with wet soil treatments ($p < 0.01$). The wet soil model across sites had an E value of 0.90 (Table 3.6) whilst the Nash-Sutcliffe value for the dry silt soil treatment was smaller at 0.84, due at least in part to the much smaller sample size (Table 3.6). For models of minimum daily temperatures, the Nash-Sutcliffe E value for the dry silt model was 0.83, which also happened to be the E value for the combined wet soil model (Table 3.6).

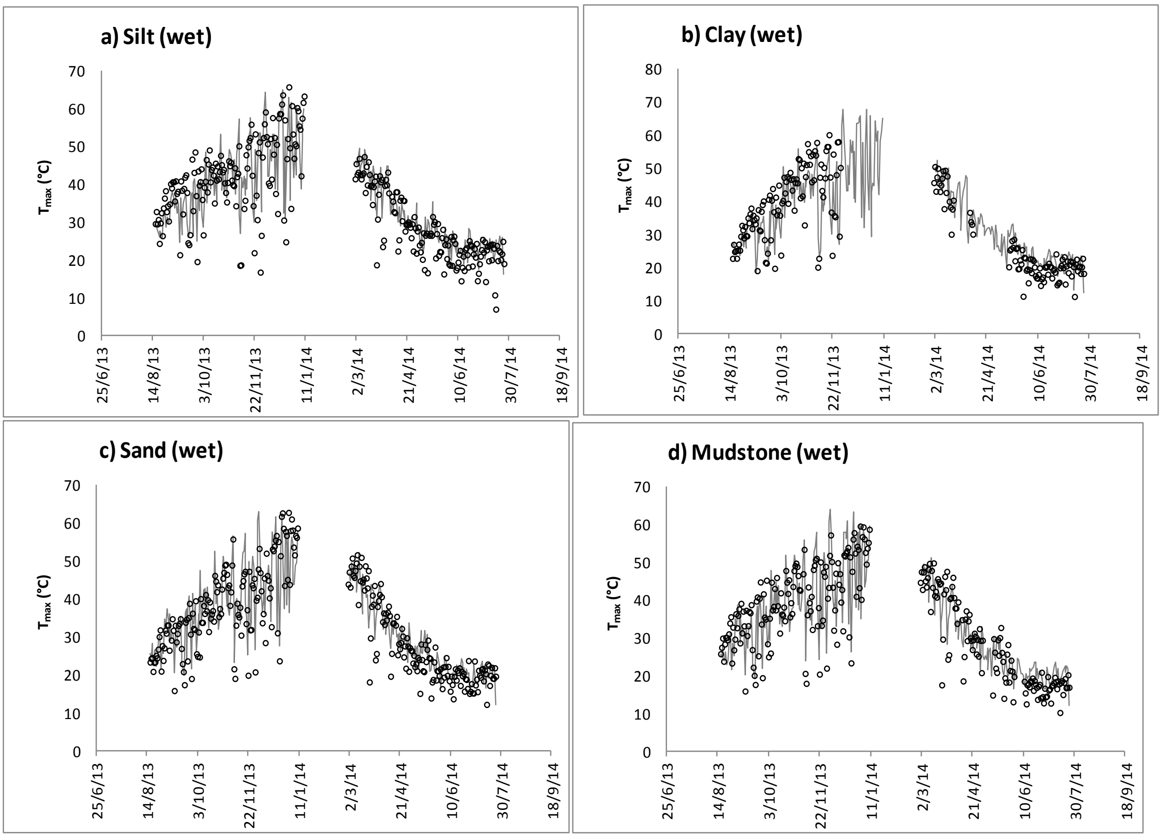


Figure 3.3 Observed (hollow points) and model (line) headspace maximum daily temperature for each of the four soil treatments. See Table 3.6 for corresponding model equations and statistics. The observed data/model gap corresponds to the temporary disabling of the trial when headspace temperatures approached/exceeded the operating limits of the climate sensors. The missing observed data for the clay treatment is due to bird damage.

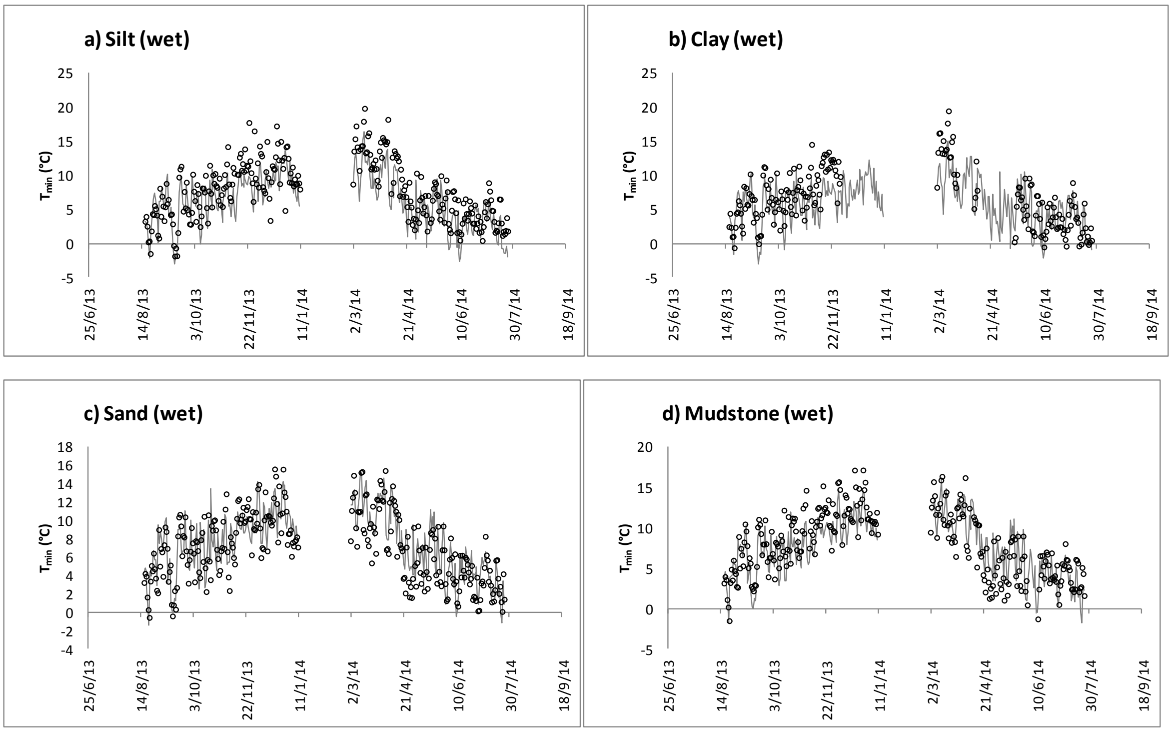


Figure 3.4 Observed (hollow points) and model (line) headspace minimum daily temperature for each of the four soil treatments. See Table 3.6 for corresponding model equations and statistics. The observed data/model gap corresponds to the temporary disabling of the trial when headspace temperatures approached/exceeded the operating limits of the climate sensors. The missing observed data for the clay treatment is due to bird damage.

Table 3.6 Model equations and performance statistics for daily headspace maximum temperature (°C) and minimum temperature (°C) for wet sand, silt, mudstone and clay soils described in Chapter 2.3.1. Collective 'all soil' regression models across all data are shown in bold text. All model coefficients are significant at the 0.01 level or lower. T_{max} = ambient daily maximum temperature, T_{min} = ambient daily minimum temperature, D = day length, R = ambient solar radiation. Lag ('X') refers to the previous day's value of the climate variable 'X'. The HS subscript refers to the headspace equivalent of the ambient climate variable.

Variable	Model	Adjusted R^2	Nash-Sutcliffe statistic E	Mean absolute deviation	Correct predictions within 95% CI
$T_{HS,max}$ Wet clay	$T_{HS,max}$ =1.227*R + 0.5684*T_{max} + 0.2264*Lag(T_{min}) + 41.40*Lag(D) - 10.25	0.94	0.94	2.38	0.96
$T_{HS,max}$ Wet silt	$T_{HS,max}$ =0.9502*R + 0.7017*T_{max} + 26.734*D – 1.038	0.87	0.89	3.09	0.98
$T_{HS,max}$ Wet sand	$T_{HS,max}$ =0.9349*R + 0.8719*T_{max} + 26.99*Lag(D) – 7.568	0.91	0.92	2.70	0.94
$T_{HS,max}$ Wet mud	$T_{HS,max}$ =1.058*R + 0.6557*T_{max} + 0.2355*Lag(T_{max}) + 20.62*Lag(D) - 5.888	0.92	0.92	2.83	0.97
$T_{HS,max}$ Wet soils	**$T_{HS,max}$ =0.9287*R + 0.9437*T_{max}- 0.2610*T_{min} – 0.0915*Lag(R) + 45.82*D – 13.19**	**0.90**	**0.90**	**3.09**	**0.94**
$T_{HS,min}$ Wet clay	$T_{HS,min}$ = 0.1743*Lag(R) + 0.9808*T_{min} - 1.566	0.78	0.79	1.52	0.98
$T_{HS,min}$ Wet silt	$T_{HS,min}$ = 0.1644*Lag(T_{max}) + 0.8566*T_{min} + 9.714*Lag(D) - 6.008	0.80	0.80	1.48	0.98
$T_{HS,min}$ Wet sand	$T_{HS,min}$ = 0.9726*T_{min} + 11.01*D - 6.681	0.86	086	1.14	0.96
$T_{HS,min}$ Wet mud	$T_{HS,min}$ = 0.909*T_{min} + 19.945*D – 9.776	0.89	0.89	1.05	0.96
$T_{HS,min}$ Wet soils	**$T_{HS,min}$ = 0.7486*T_{min} + 0.1147*Lag(T_{max}) + 15.32*Lag(D) – 8.353**	**0.83**	**0.83**	**1.34**	**0.95**
$T_{HS,min}$ Dry silt	$T_{HS,min}$ = 0.8818*T_{min} + 22.84*Lag(D) – 11.25	0.84	0.85	1.39	0.96
$T_{HS,max}$ Dry silt	$T_{HS,max}$ =1.262*R + 0.7045*T_{max} + 69.22*Lag(D) – 12.146	0.84	0.84	3.46	0.94

3.4.3 Daily Distribution of Headspace Temperature

Seasonal variations in the daily distribution of indexed headspace temperatures were observed to occur for all film treatments (e.g. Figure 3.5 for the wet mudstone treatment). These variations were associated with seasonal changes in solar radiation intensity and day length, and were most pronounced during time-points 2-4, with time-points 1 and 5-8 demonstrating minimal seasonality. Seasonal variations in daily temperature distribution across each of the three-hour subsets were able to be predicted across each of the four soil treatments (Figure 3.5). Diurnal temperature fluxes occurred faster than predicted by the APSIM model, hence predicted cumulative heat exposure throughout the day was overestimated, particularly between time-points 2-5 (Figure 3.5).

An alternative model was developed from 10-minute temperature observations described in Chapter 2, and is presented in Equation 3.1. This model was shown to have greater accuracy than the APSIM model across all three-hourly time-points (Figure 3.6). Temperature differences between this model and the APSIM model were largest during time-points 2-5, during which the APSIM model was least accurate (Figure 3.5). Differences between these models at these time-points varied between 0.4 °C during winter (time-point 5) to 8.6 °C during summer (time-point 3) (Figure 3.7).

$$T_n = 1.011926\, T_{min} + 1.484743\, \Delta T_{diff} - \sqrt{n}\,(0.559607\, T_{diff} + 1.155245) \qquad \text{(Eq. 3.1)}$$

where: n is an integer; $n \in \{1, 2, 3, \dots, 8\}$

T_n = median temperature for timepoint n

T_{min} = daily temperature minimum

T_{max} = daily temperature maximum

$T_{diff} = T_{max} - T_{min}$

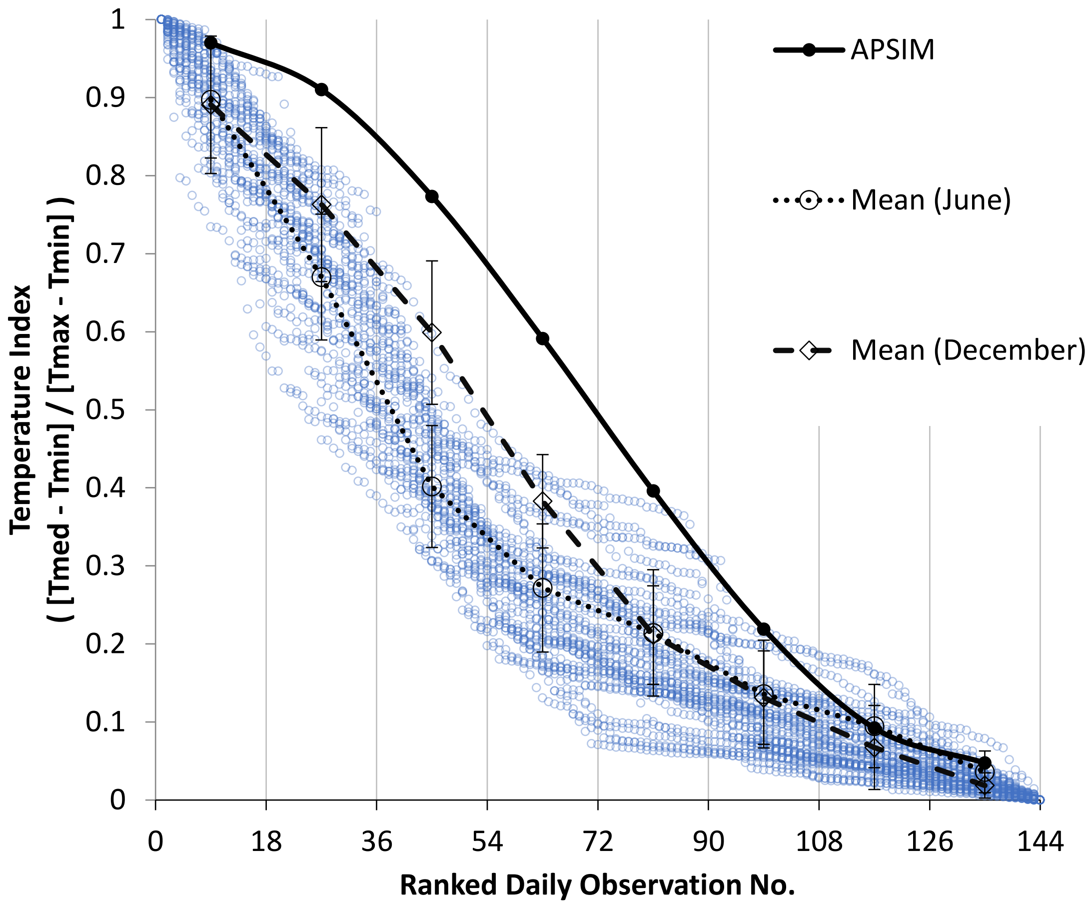


Figure 3.5 Median three-hourly temperatures estimated by APSIM (black hollow points), as well as median three-hourly temperature observations during winter (June) and summer (December) beneath clear polymer film for the wet mudstone treatment. Ten-minute temperature observations are depicted in blue.

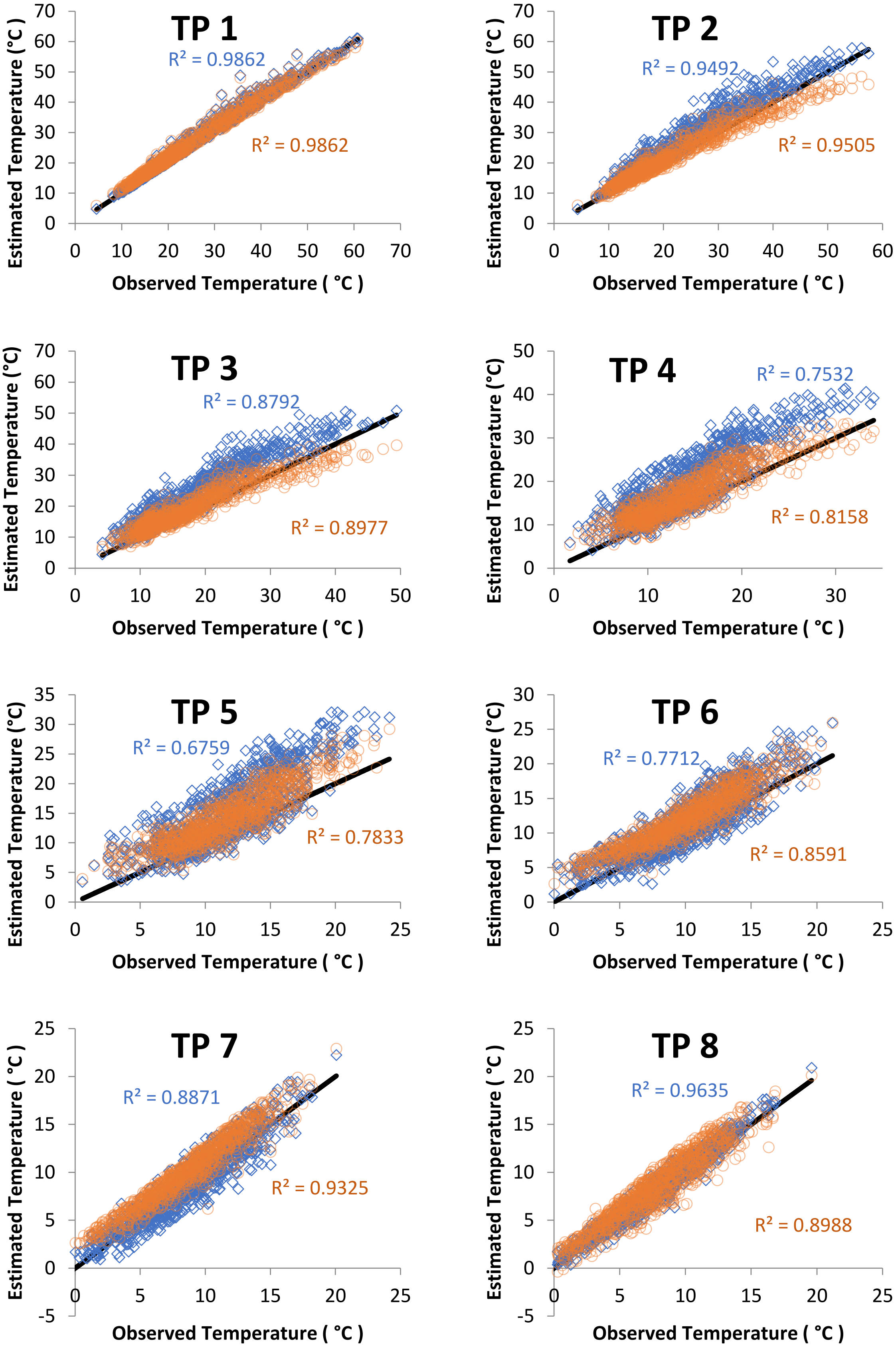


Figure 3.6 Estimated three-hourly median temperatures using the APSIM (blue) and statistical model (orange) at the eight time-points presented in Figure 3.5. Outputs from these models are contrasted to observed temperatures for the mudstone treatment (black line).

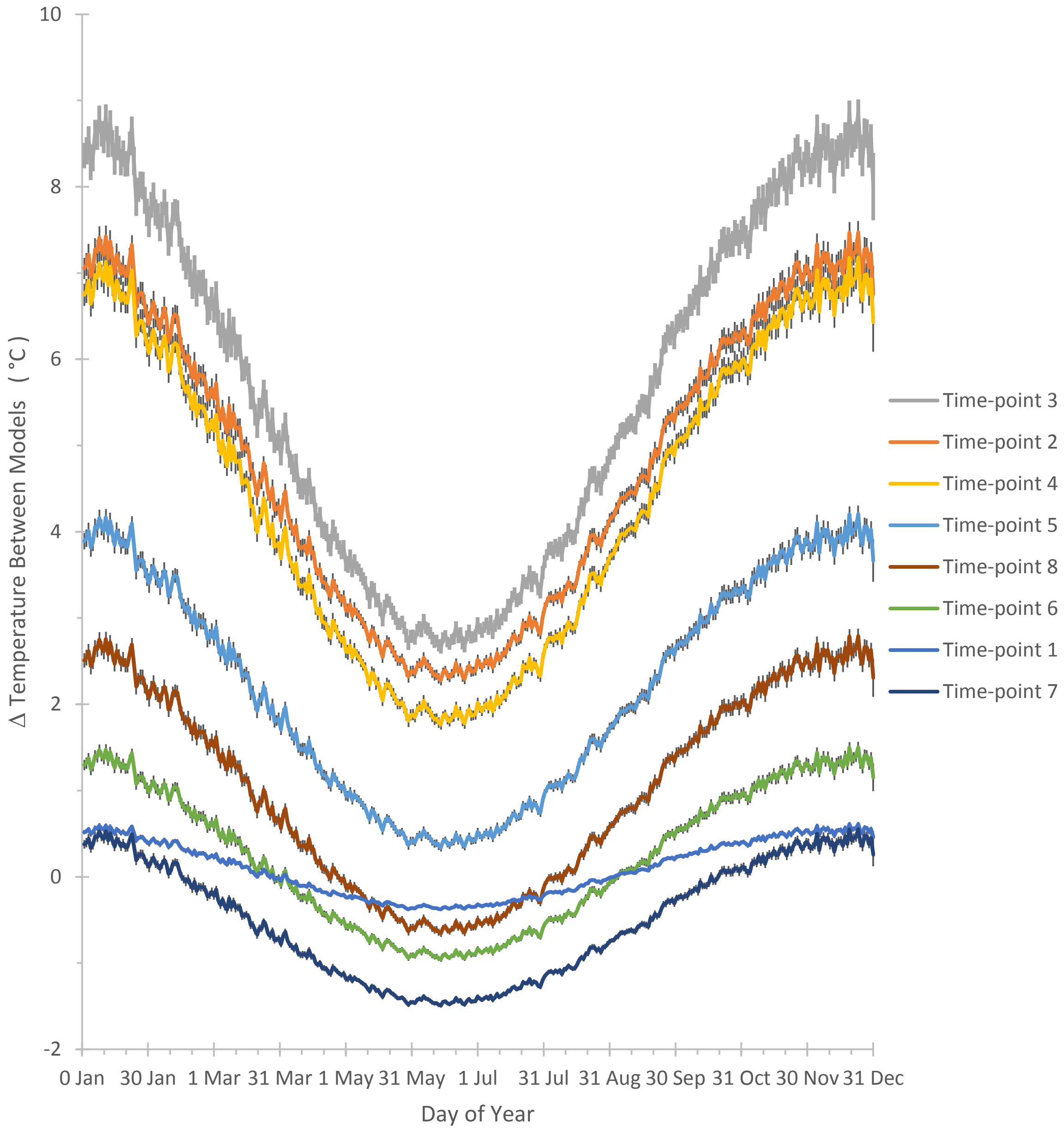


Figure 3.7 Mean seasonal differences in three-hourly median headspace temperature between the statistical model presented in Table 3.4 (baseline) and APSIM's inbuilt temperature interpolation model. Line colour denotes three-hourly time-point. Bars represent SEM.

3.4.4 Thermal Suitability of Film for Temperate Crop Production in Tasmania

Film use improved temperatures for temperate crop production between late-autumn and early-spring across all sites. By combining the daily temperature interpolation model presented in Equation 3.1, the thermal time model presented in Table 3.1, and the radiation use efficiency model presented in Table 3.2, film was predicted to have beneficial effects upon temperate crop RUE between mid-April and early-September due to increased headspace temperatures. Film use increased radiation use efficiency between mid-April and early-September when simulating crop suitability using the APSIM temperature interpolation model (Figure 3.8). Outside of this window, the APSIM temperature interpolation model predicted that film would have detrimental effects upon crop RUE due to high probability of heat stress (Figure 3.9).

Temperature conditions created by film use also able to support faster rates of crop ontogenic development between mid-March and early-November by increasing opportunities for crop thermal time accumulation in temperate crop species (Figure 3.10). The benefits from film use were largest between late-May and mid-July, when film use did not cause crops to experience heat-stress conditions (Figure 3.11) and ambient crop development was constrained by cold (Figure 3.12). Outside of this 2-month winter period, film use caused temperate crops to experience transient heat stress on a daily basis which partially offset the benefits provided by film use.

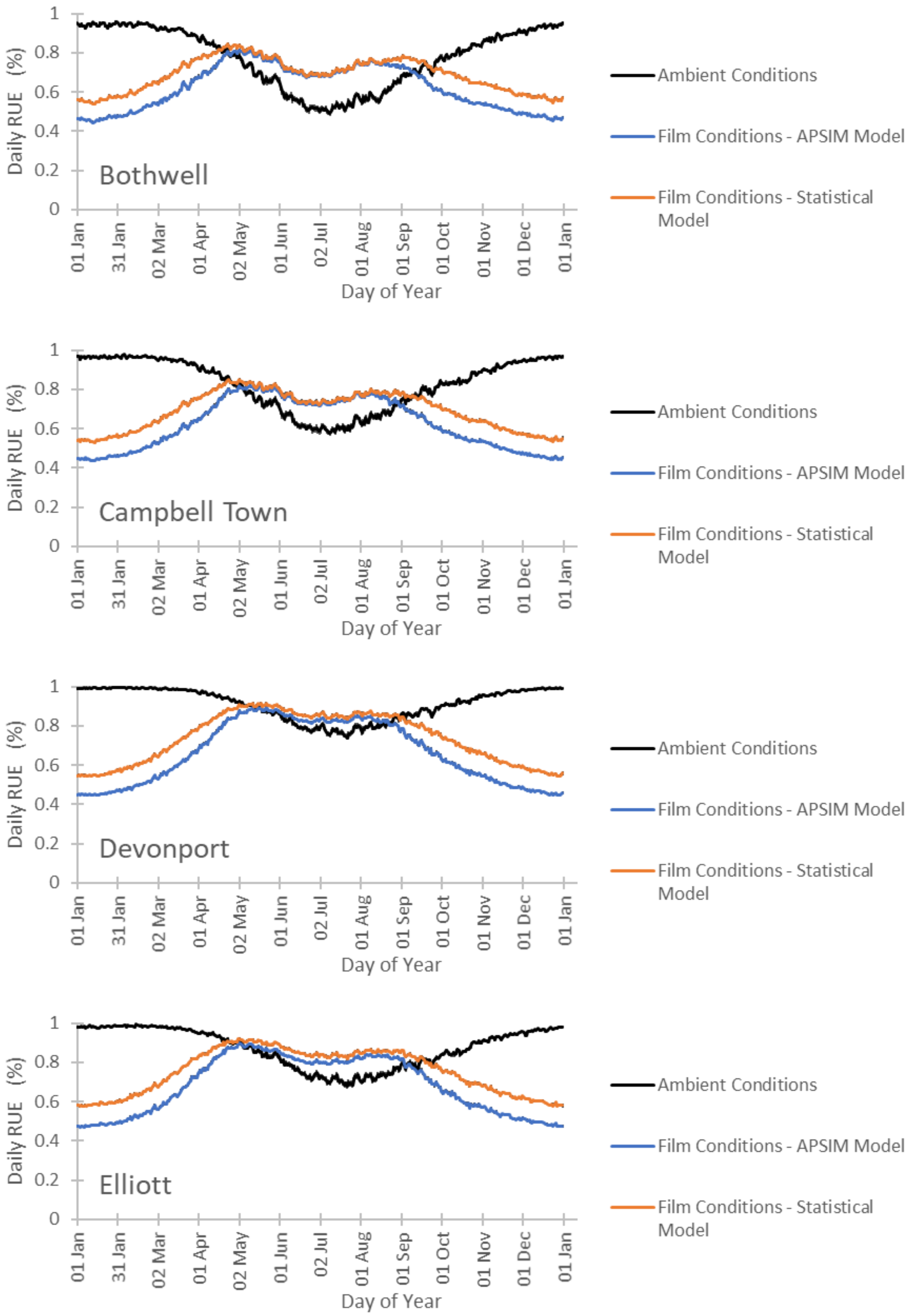


Figure 3.8 Maximum daily thermal limit of solar radiation use efficiency (RUE) in wheat growing at Bothwell, Campbell Town, Devonport and Elliott. Coloured lines represent the maximum daily RUE of crops using the daily temperature interpolation models (APSIM and statistical) discussed above. The black line represents the maximum daily RUE of crops growing without film. Values represent mean no. of degree days ± SEM.

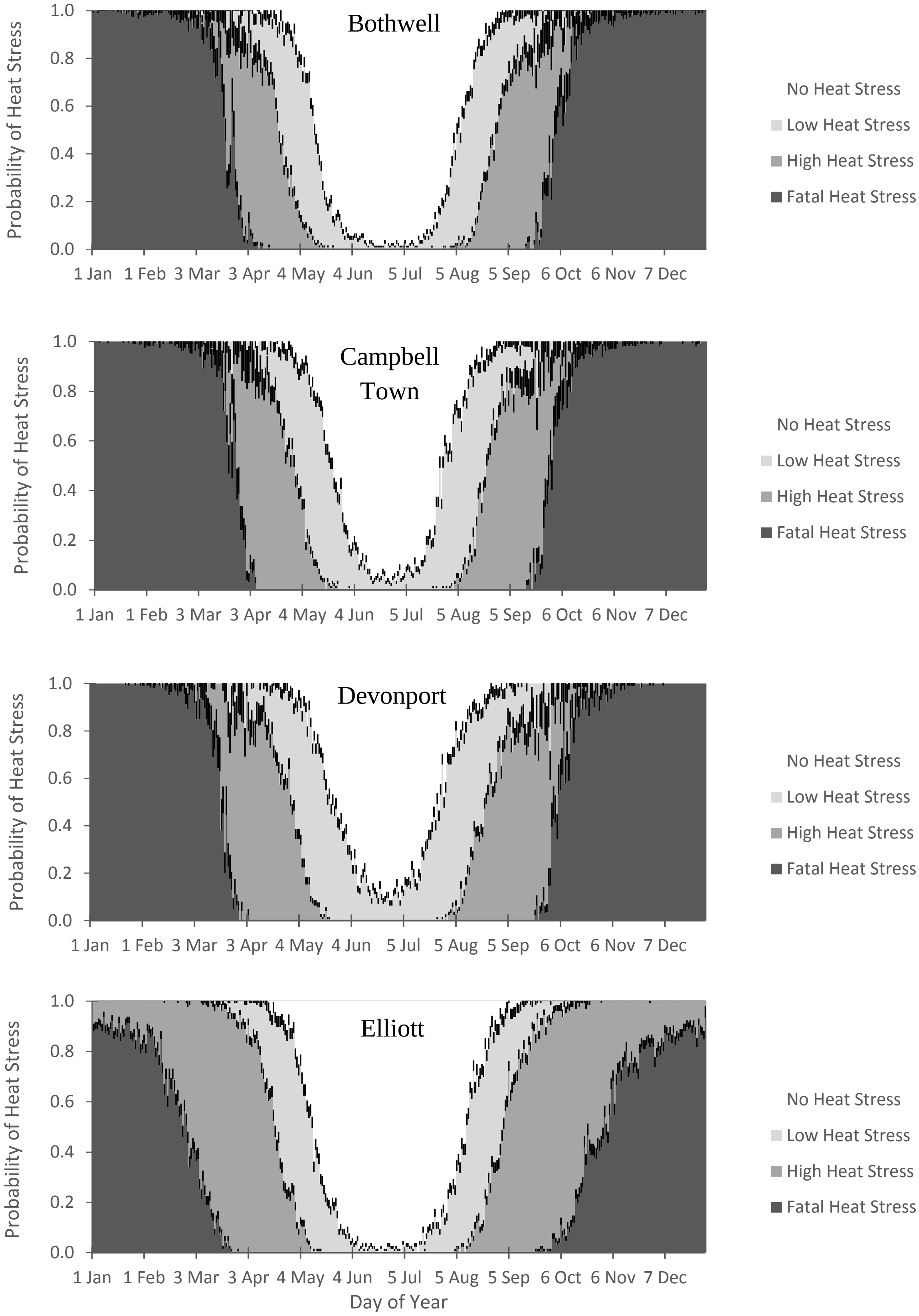


Figure 3.9 Probability that maximum daily temperatures under film cause no heat stress (<25 °C), low heat stress (25-30 °C), high heat stress (30-45 °C), or potentially fatal heat stress (>45 °C) to wheat growing beneath film at Bothwell, Campbell Town, Devonport, and Elliott from 1889 to 2015. Values represent mean probability + SEM.

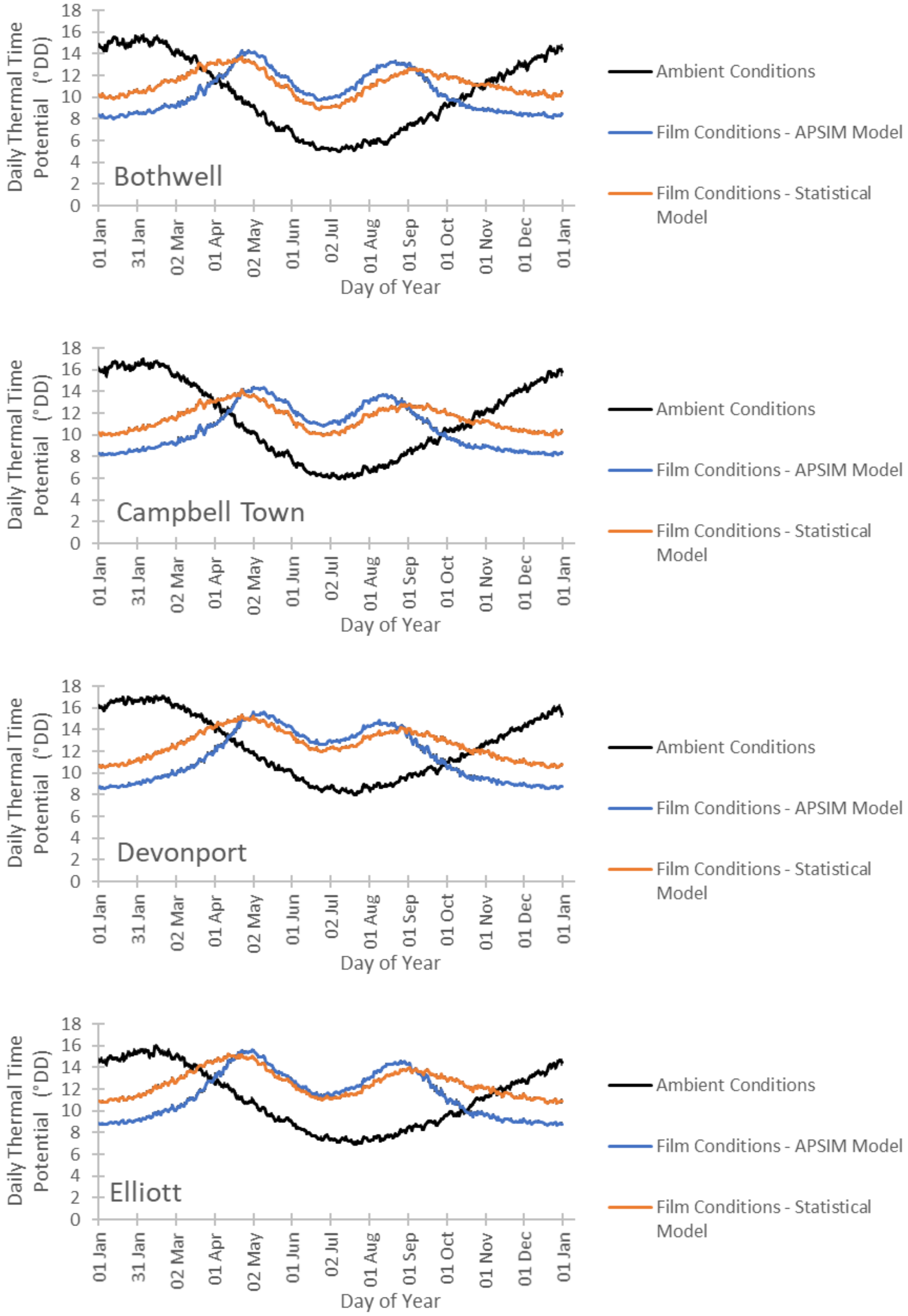


Figure 3.10 Potential thermal time (°DD) for wheat and similar temperate crops growing under film at Bothwell, Campbell Town, Devonport and Elliott. Coloured lines represent the mean units of thermal time lost by crops using the daily temperature interpolation models (APSIM and statistical) discussed above. The black line represents the mean units of thermal time lost by crops growing without film. Values represent mean no. of degree days ± SEM.

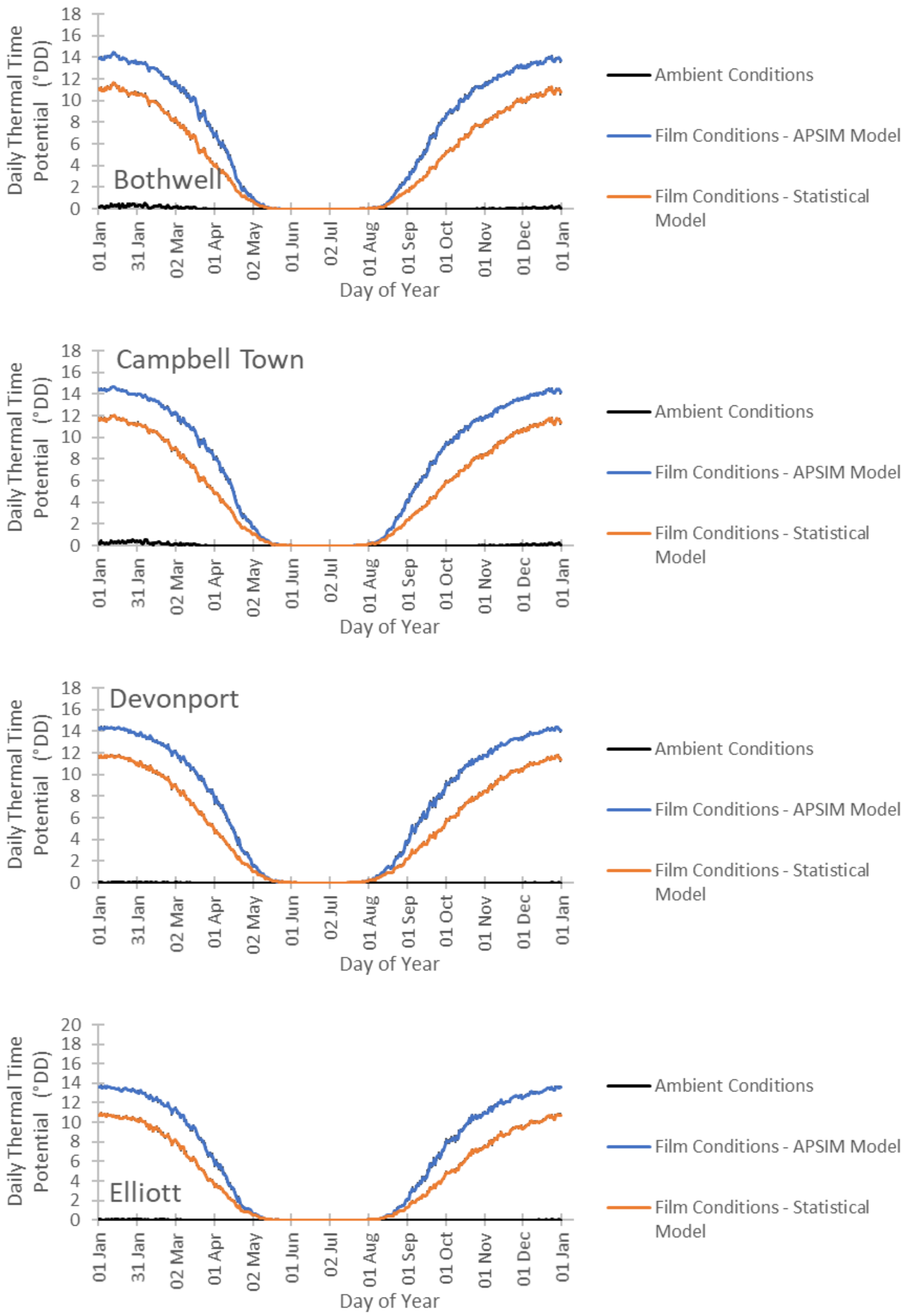


Figure 3.11 Predicted daily thermal time (°DD) lost by temperate crops due to supra-optimal temperatures at Bothwell, Campbell Town, Devonport and Elliott. Coloured lines represent the mean units of thermal time lost by crops using the daily temperature interpolation models (APSIM and statistical) discussed above. The black line represents the mean units of thermal time lost by crops growing without film. Values represent mean no. of degree days ± SEM.

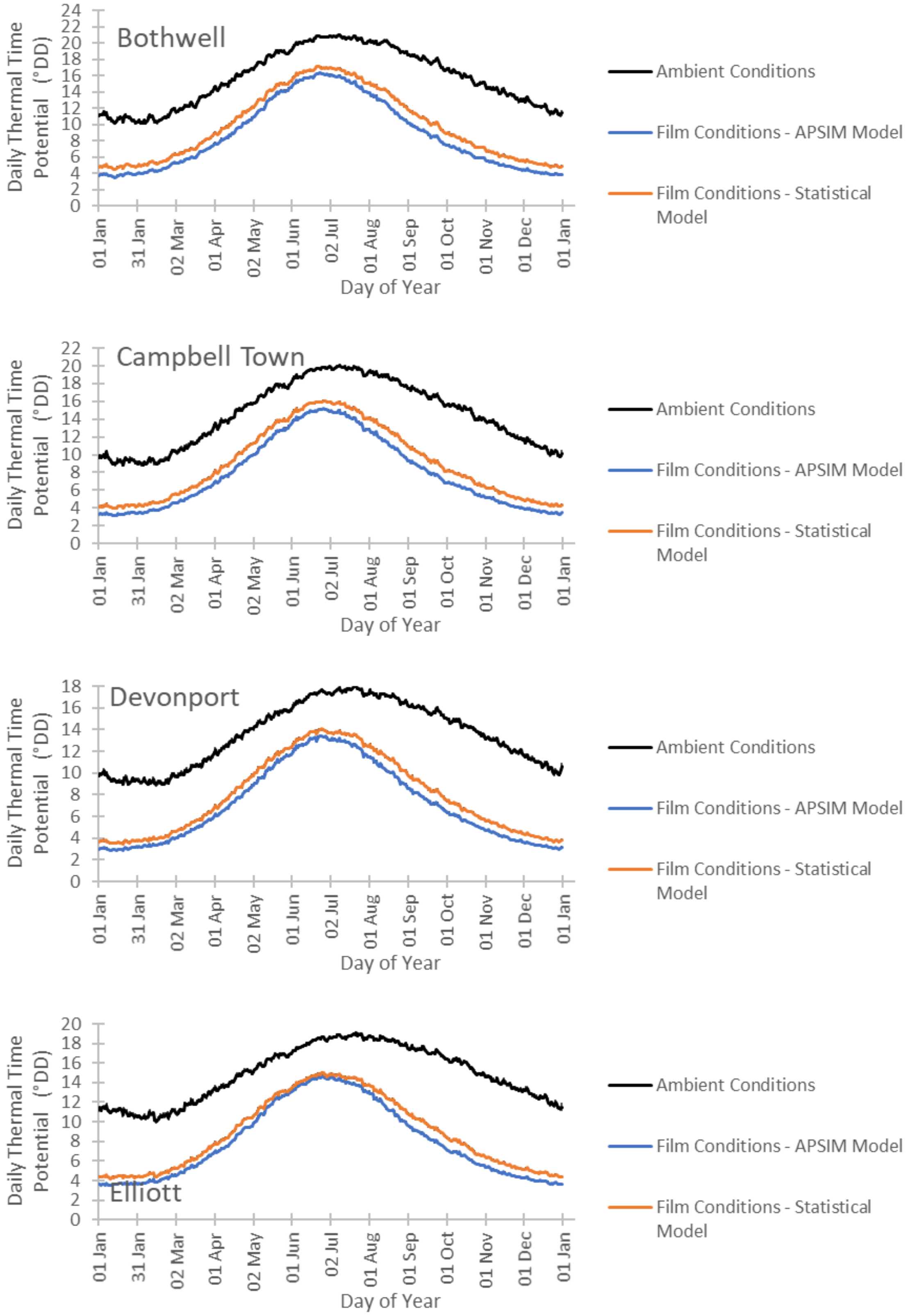


Figure 3.12 Predicted daily thermal time (°DD) lost by temperate crops due to sub-optimal temperatures at Bothwell, Campbell Town, Devonport and Elliott. Coloured lines represent the mean units of thermal time lost by crops using the daily temperature interpolation models (APSIM and statistical) discussed above. The black line represents the mean units of thermal time lost by crops growing without film. Values represent mean no. of degree days ± SEM.

3.4.5 Thermal Suitability of Film for Tropical Crop Production in Tasmania

Film use improved temperatures for tropical crop production between late-autumn and early-spring across all sites. Increased headspace temperatures created through film use were predicted to have beneficial effects upon tropical crop RUE between late-February / mid-March and late-December (Figure 3.13), despite high probability of heat stress (Figure 3.14). When simulating crop suitability using the APSIM temperature interpolation model, film use increased radiation use efficiency between early-March and mid-November, had beneficial effects upon crop thermal time accumulation between late-February and early-December. Outside of this window, the APSIM temperature interpolation model predicted that film would have detrimental effects upon crop RUE and thermal time accumulation due to longer exposure to heat stress conditions.

Temperature conditions created by film use also able to support faster rates of crop thermal time accumulation throughout the year (Figure 3.15) by reducing the effects limitations caused by cold ambient temperatures (Figure 3.16). These benefits from film use were largest during two periods; between early-March and late-April, and between mid-August and late-November. Between these periods, thermal time accumulation was still highly limited by cold stress in winter (Figure 3.16) and heat stress in summer (Figure 3.17). In regions like Bothwell and Campbell Town, which frequently experience spring frost (Figure 3.18), early removal or degradation of film during this period to reduce heat stress may cause crops to become exposed to frost damage.

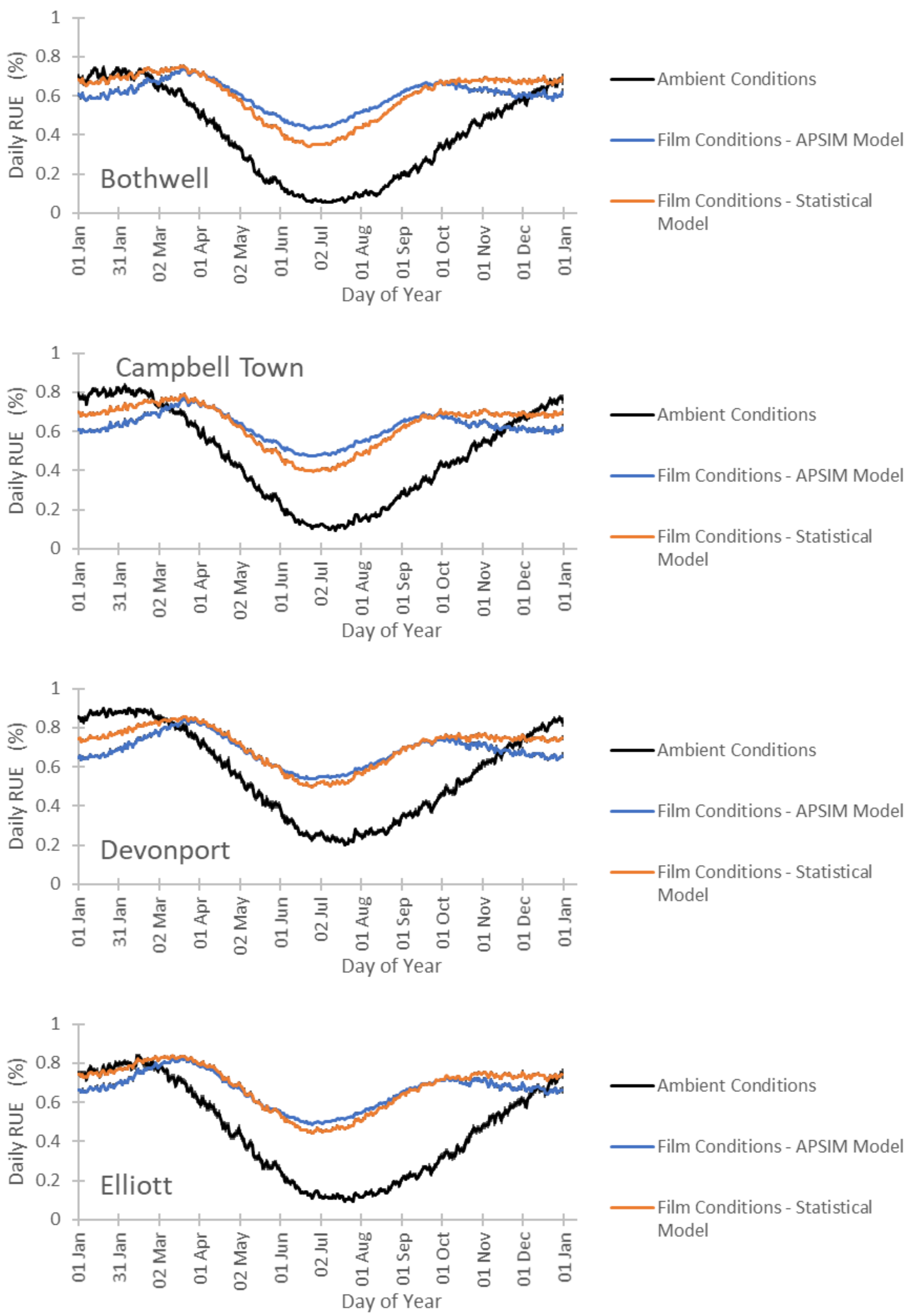


Figure 3.13 Maximum daily thermal limit of solar radiation use efficiency (RUE) in maize growing at Bothwell, Campbell Town, Devonport and Elliott. Coloured lines represent the maximum daily RUE of crops using the daily temperature interpolation models (APSIM and statistical) discussed above. The black line represents the maximum daily RUE of crops growing without film. Values represent mean no. of degree days ± SEM.

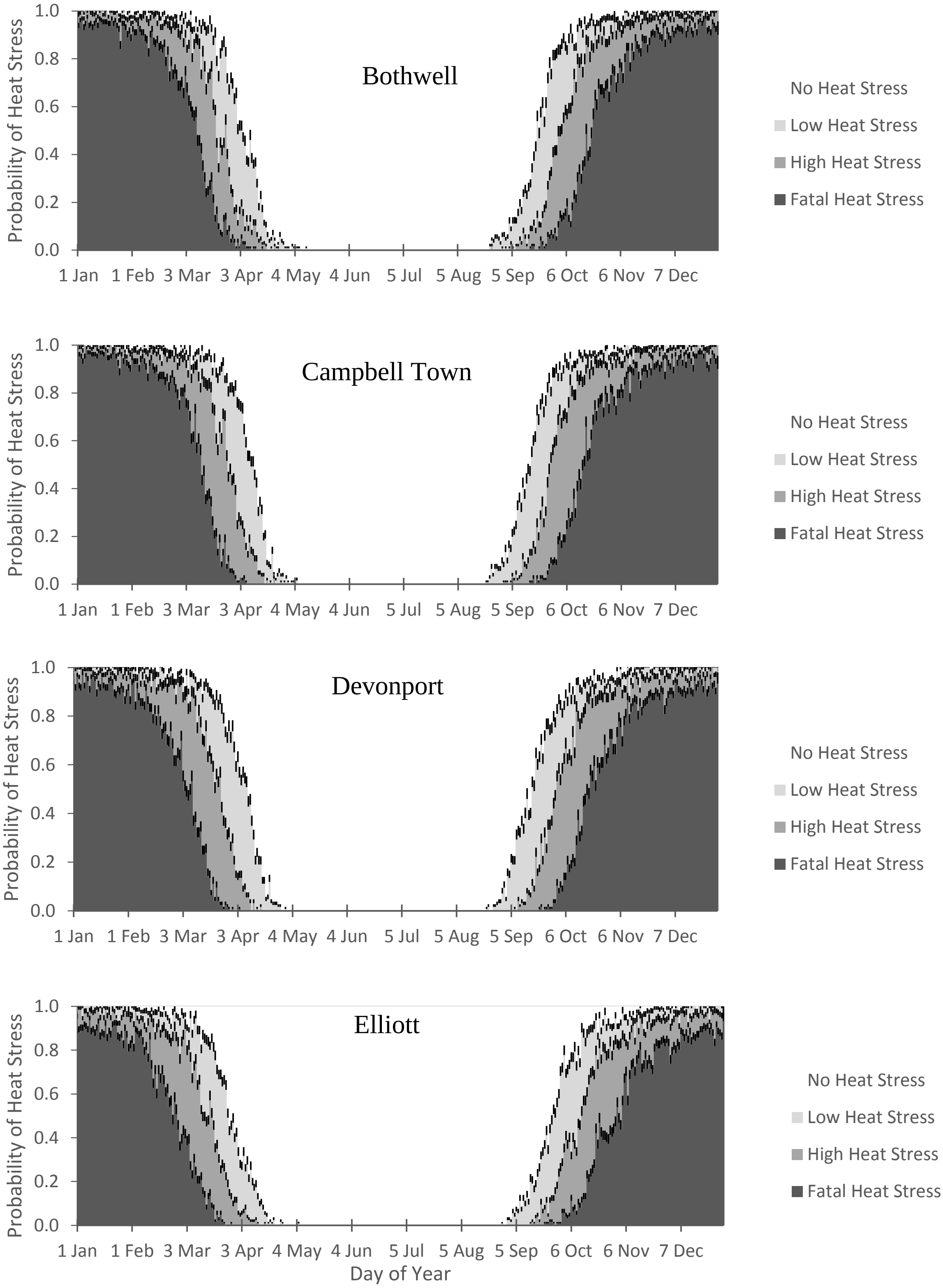


Figure 3.14 Probability that maximum daily temperatures under film cause no heat stress (<36 °C), low heat stress (36-40 °C), high heat stress (40-45 °C), or potentially fatal heat stress (>45 °C) to maize growing beneath film at Bothwell, Campbell Town, Devonport, and Elliott over the period 1889 to 2015. Values represent mean probability + SEM.

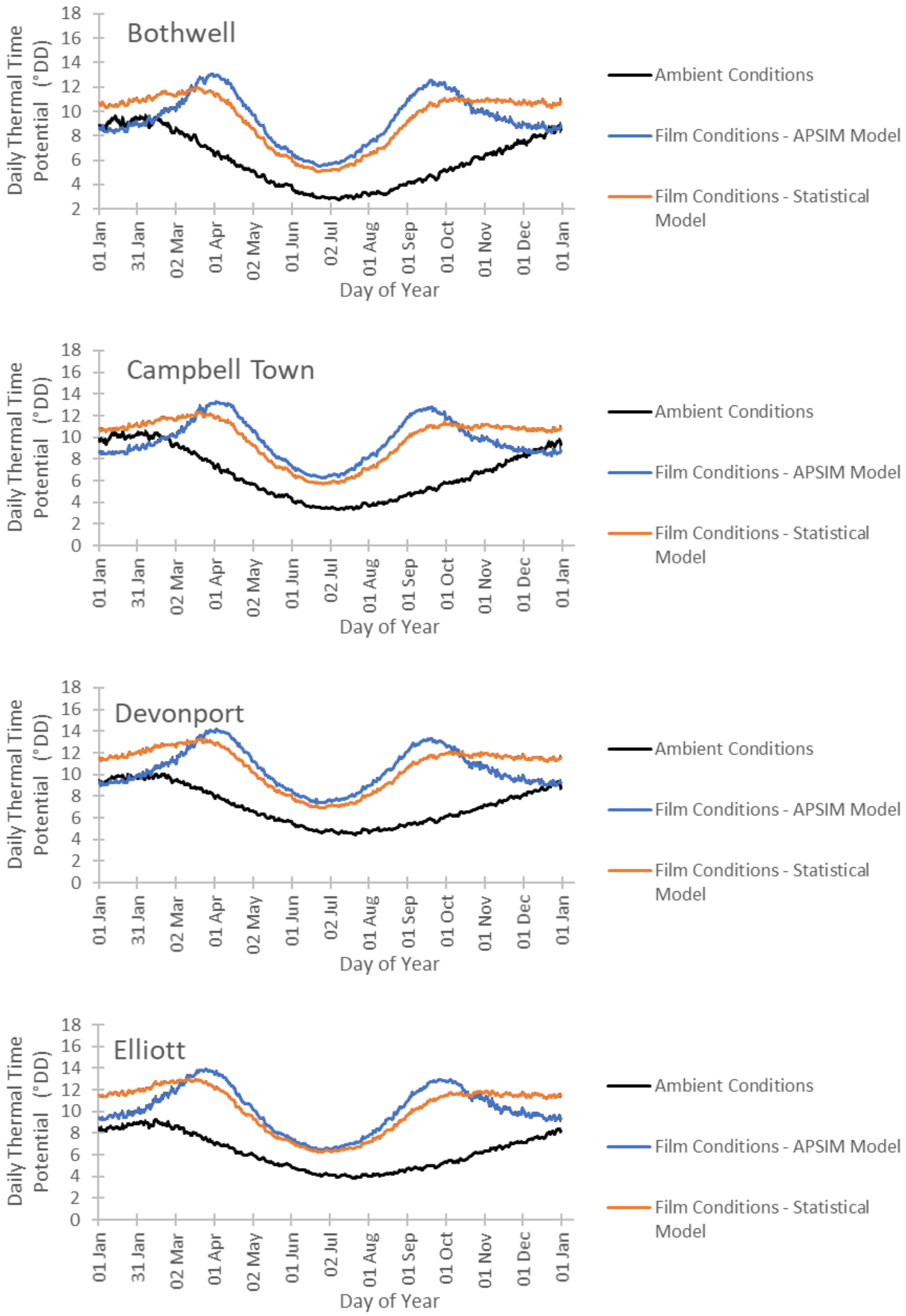


Figure 3.15 Potential thermal time (°DD) for maize and similar tropical crops growing under film at Bothwell, Campbell Town, Devonport and Elliott. Coloured lines represent the mean units of thermal time lost by crops using the daily temperature interpolation models (APSIM and statistical) discussed above. The black line represents the mean units of thermal time lost by crops growing without film. Values represent mean no. of degree days ± SEM.

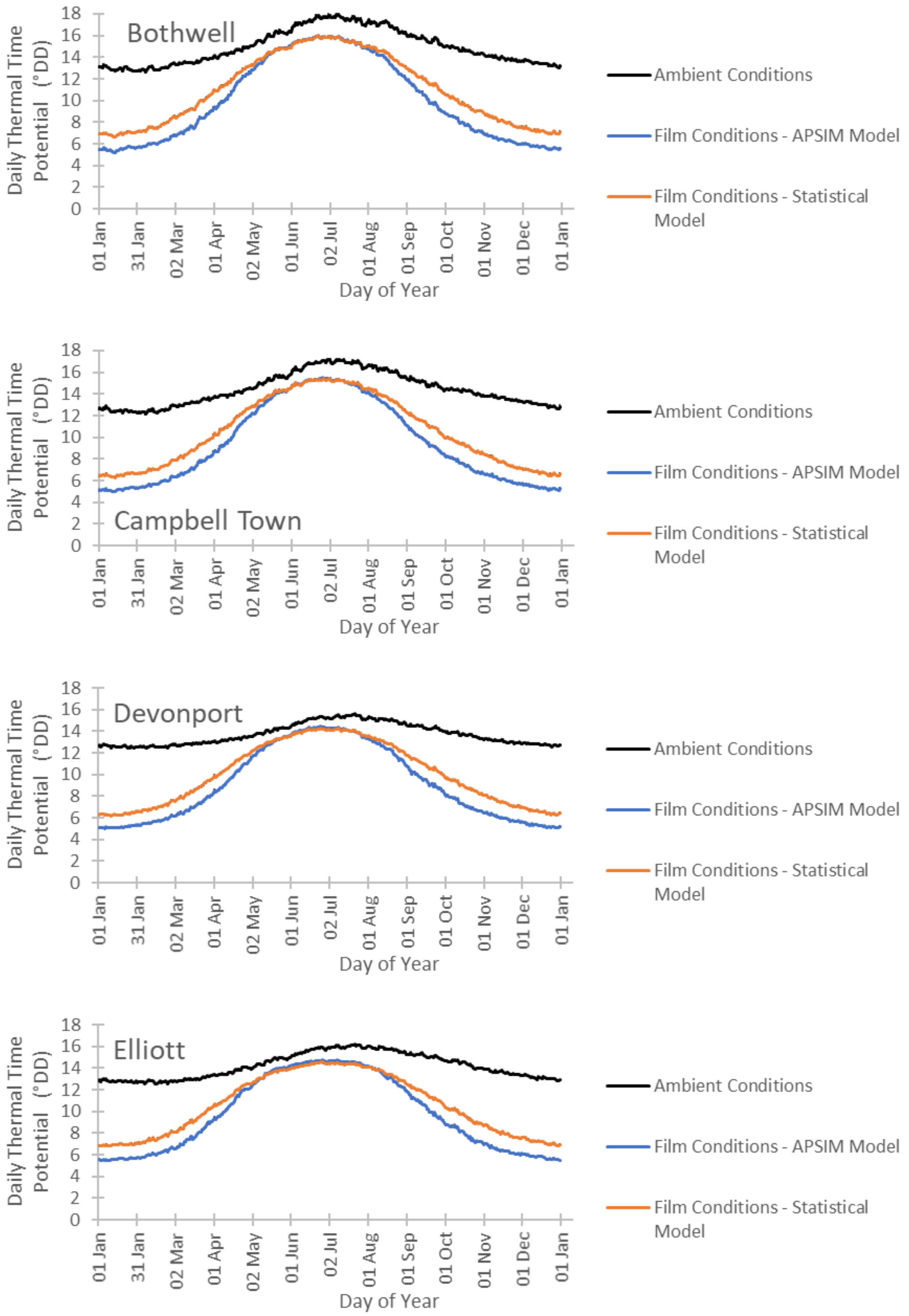


Figure 3.16 Predicted daily thermal time (°DD) lost by maize crops due to sub-optimal temperatures at Bothwell, Campbell Town, Devonport and Elliott. Coloured lines represent the mean units of thermal time lost by crops using the daily temperature interpolation models (APSIM and statistical) discussed above. The black line represents the mean units of thermal time lost by crops growing without film. Values represent mean no. of degree days ± SEM.

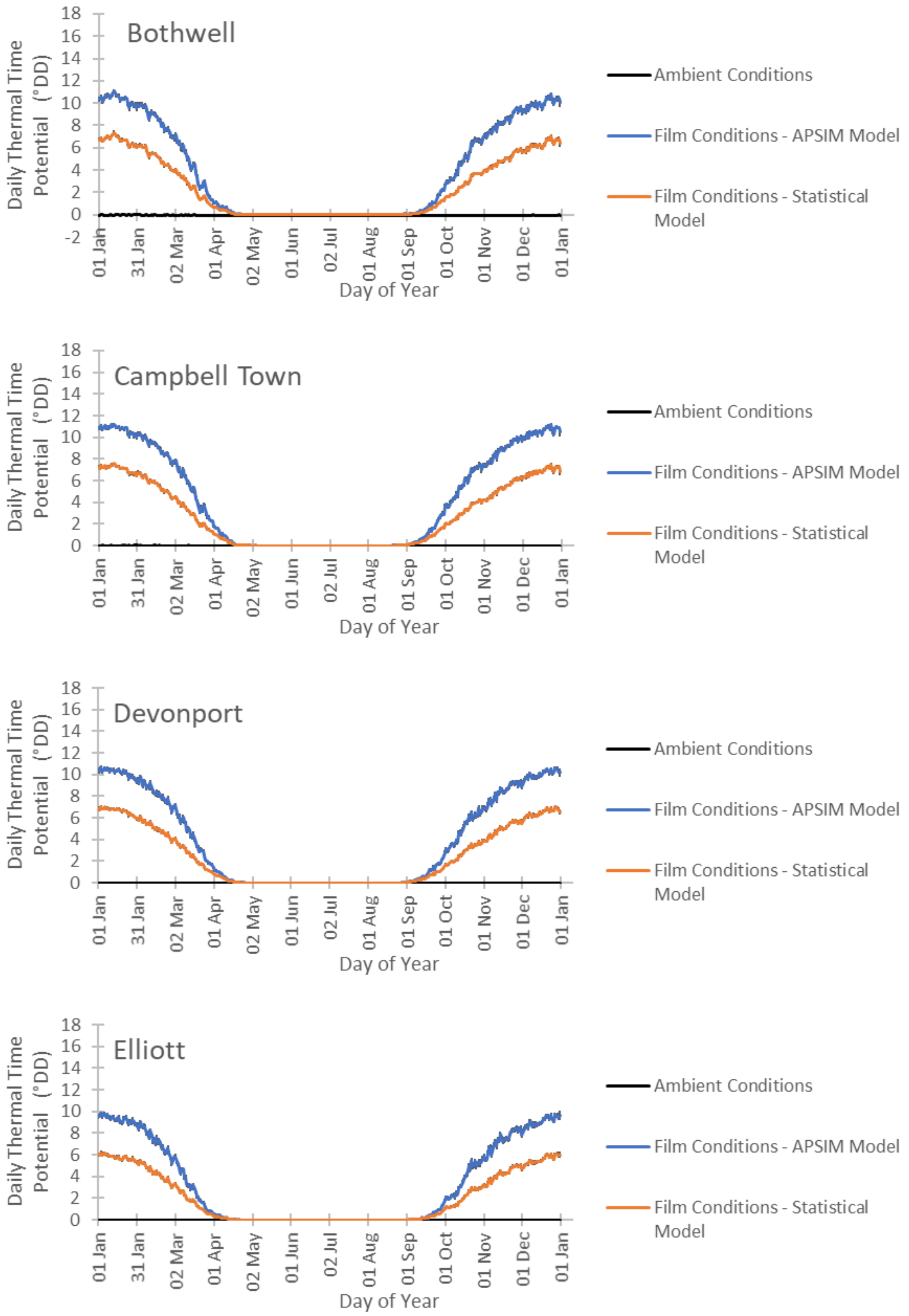


Figure 3.17 Predicted daily thermal time (°DD) lost by maize crops due to supra-optimal temperatures at Bothwell, Campbell Town, Devonport and Elliott. Coloured lines represent the mean units of thermal time lost by crops using the daily temperature interpolation models (APSIM and statistical) discussed above. The black line represents the mean units of thermal time lost by crops growing without film. Values represent mean no. of degree days ± SEM.

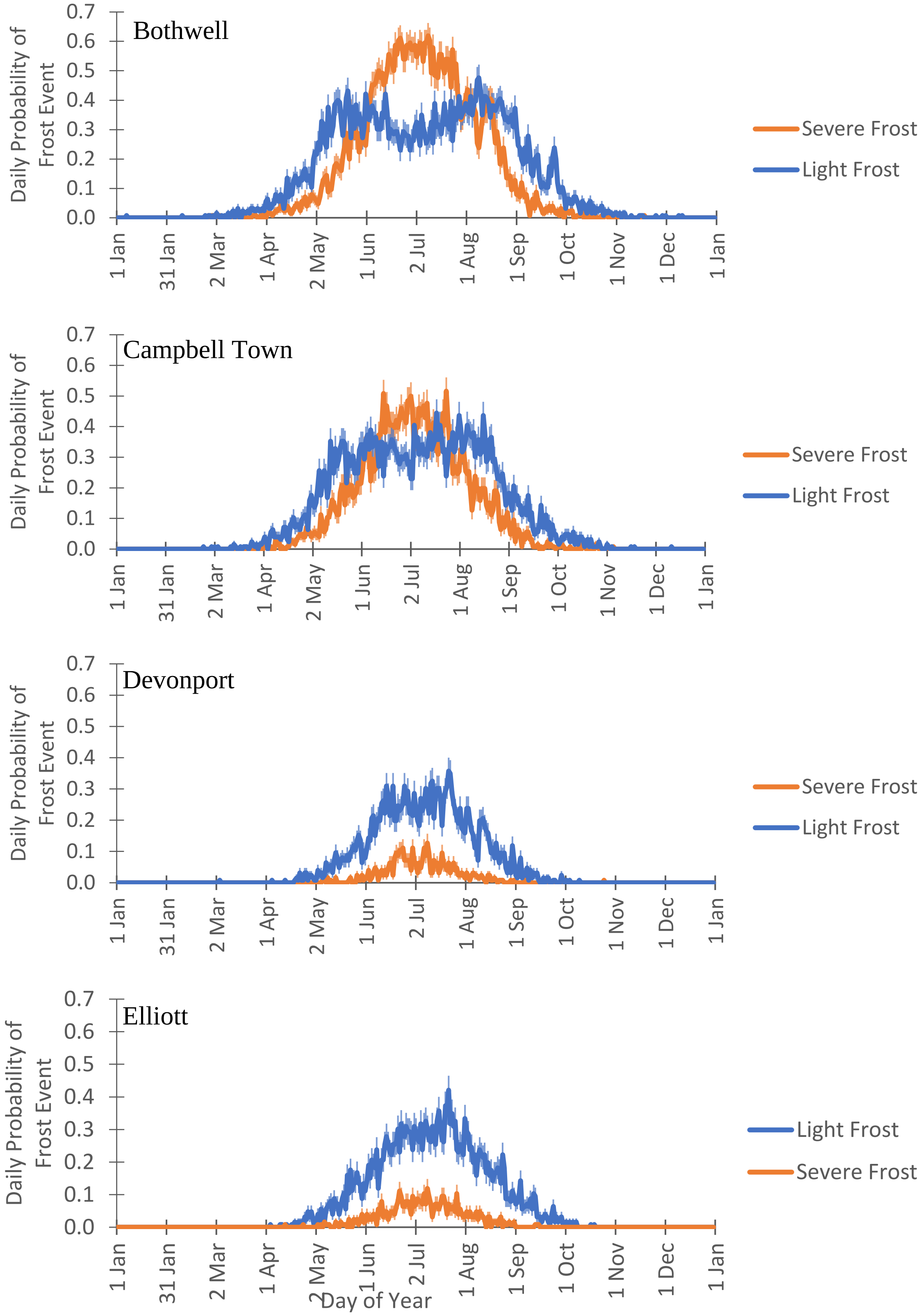


Figure 3.18 Daily frequency of meteorological conditions permitting frost formation at Bothwell, Campbell Town, Devonport, and Elliott over the period 1889 to 2015. Values represent mean daily probability ± SEM.

3.5 Discussion

Film is predominately used by agricultural producers to enable earlier crop emergence and faster seedling growth in environments that are otherwise constrained by frost and low temperatures. Industry uptake and adoption of film for crop production will depend on the technology's capacity to safely create suitable conditions to support early plant growth autumn, winter and spring when ambient temperature conditions are sub-optimal for crop growth.

Heat stress exposure was identified as the major limitation to film use in Tasmania for all crop types. Heat stress exposure inhibits crop biomass production and development, which is captured in within the APSIM model by reducing crop rates of RUE and thermal time accumulation, and by increasing rates of leaf death and abscission (Brown et al., 2014). In extreme cases, crop heat stress may result in crop death if the severity and duration of crop exposure to fatal temperatures exceeds biologically-derived maximum temperature thresholds. For most plant species, the maximum sustained temperature that can be survived is confined to a relatively narrow range of 40 to 45 °C, beyond which the denaturation of key growth enzymes will lead to plant death (Corkrey *et al.*, 2014). However, maximum temperature thresholds for a given species or cultivar can vary in response to the duration and severity of heat stress exposure, as well as the efficacy of various thermo-tolerance mechanisms (Senioniti *et al.*, 1986). These mechanisms may be influenced by other environmental conditions including the high [CO_2] present beneath the film, which reduces stomatal activity and the tissue-cooling effects which depend upon transpiration rate (Heins *et al.*, 1984; Burke and Upchurch, 1989; Seginer 1994).

In this chapter, the inbuilt temperature interpolation model used by APSIM was shown to be a poor predicter of the duration and severity of heat stress severity and duration beneath film, and an improved temperature interpolation model was developed to improve these predictions. Differences between the two models reflected differences in the duration of time that crops were expected to be exposed to elevated temperatures. Comparison between these models showed that the APSIM model overestimates crop heat exposure and crop development during 12 hours of each day (37.5-87.25 percentiles). When applied to RUE and thermal time temperature response curves used by APSIM, this led to overestimation of RUE and thermal time accumulation during the cold winter months, and underestimation of crop potential RUE and thermal time accumulation for crops experiencing heat stress across all sites.

Due to these inaccuracies, improvements in daily temperature modelling described in this chapter represent an important step for estimating crop growth and development under film. The capacity to model these environmental variables may in time provide a potential mechanism for predicting the lifespan of the above- and below- ground (i.e. buried) portions of film, and hence identify the most appropriate film formulation and film management regime for a given application. Headspace and soil temperatures strongly influence rates of film degradation above and below the soil (Ammala *et al.* 2011), as well as a range of other processes such as soil respiration (which influences CO_2 levels). Ultimately, determining the optimal duration of film use is dependent on an individual film users' attitudes toward risk, which is at least partially influenced by the level of control exerted by the film user over the film degradation/removal process (Gilead 1995). Film users seeking to incorporate *in situ* degradable films (e.g. bio-, oxo- and/or thermo-degradable films) may enjoy additional financial benefits including reduced abrasion and damage to crops during film removal and decreased labour and film waste disposal costs (Kasirajan and Ngouajio, 2012) if film degradation can be tailored to coincide with crop development and seasonal weather conditions.

Simulations of headspace conditions under film indicated that Tasmanian producers of tropical cereals may benefit significantly from film use. Due to the high heat tolerance of tropical species, the safe operating window for film use extended between March and November. Film use was associated with large improvements in crop RUE of up to 285% during August, 178% in September, and 93% in October, enabling more efficient biomass production and improved productivity (Maddonni 2012). Film use was also associated with higher potential rates of thermal time accumulation for tropical cereal crops, which promotes faster emergence and rapid phenological development than is possible under ambient conditions (Maddonni 2012). Increases in potential thermal time accumulation resulting from film use were largest during August-October (106% above ambient) and mid-February until early-May (63% above ambient). Outside of these periods, increases in potential thermal time accumulation were more modest at 30-40% above ambient rates. Despite being highly susceptible to frost (Lindow 1983), temperature increases from film use in winter were sufficient to consider cultivation of these species even during winter months, where they are likely to benefit from film's capacity to protect enclosed seedlings from frost exposure (Orzolek 2017). During summer, film use is likely to be detrimental due to the increasing duration and severity of heat stress conditions present beneath film, and the increasing thermal suitability of ambient temperature conditions for thermal time accumulation.

In contrast to the potential benefits experienced by tropical cereals, environmental simulations indicated that film could only be safely used with temperate crop species for four months of the year centred around the winter solstice. During this safe period of use, film increased mean maximum daily temperatures by 12 °C, increasing the potential for these crops to thermal time accumulation rates by 70-80 % above ambient and shield crops from frost damage. Outside of this winter period, film use can cause headspace temperatures to exceed optimal growing temperatures under some conditions (Stapleton and DeVay, 1984; Stapleton and DeVay, 1986), causing crops growing beneath the film to experience severe heat stress. Warmer conditions created through film use are also able to create modest increases in RUE (26 % ± 0.8 % above ambient), although these increases were offset by film-induced solar radiation attenuation. Due to these limitations, temperate cereals are unlikely to benefit significantly from film use in Tasmania.

3.6 Conclusions

In this chapter, simple models were derived for predicting the maximum temperature, minimum temperature, and daily solar radiation exposure within the film-enclosed headspace from ambient climate equivalents and day length. Such models can be used: to predict broader system responses to film; in identifying site-specific operational limits for film application; and in predicting times for film degradation.

Using these models it was shown that film use created temperature conditions too hot for temperate cereal production, but produced temperature conditions suitable for tropical cereals. Due to the unsuitability of film use for temperate cereals, the remainder of this thesis will focus on tropical cereals, using maize as a model species. This work will explore the agronomic and photosynthetic characteristics of maize grown within a film-enclosed growing environment, and how these parameters are influenced by rapid diurnal fluctuations in headspace temperatures, solar radiation intensity, and [CO_2]. These conditions are not easily replicable using existing infrastructure (e.g. phytotrons and growth cabinets) designed to maintain thermal, spectral, and atmospheric stability, so the development of suitable equipment to enable physiological observations is presented and discussed next in Chapter 4.

Chapter 4: Development of a Film-enclosed Controlled Environment Chamber Network

4.1 Abstract

Film use has been proposed as a low-cost means of increasing crop productivity and water use efficiency for broad-acre agricultural and horticultural applications in southern Australia. Enclosure of the headspace with film alters environmental conditions beneath the film layer. Existing models of crop growth and development have been characterised and developed from datasets collected under ambient growing conditions, which may not be representative of seedlings growing within a film-enclosed headspace.

In this chapter, designs and performance testing of film-enclosed growing chambers suitable for replicating film-enclosed headspace conditions are discussed. During uniformity testing, temperatures did not vary significantly between chambers, with soil and headspace air temperatures remaining similar amongst all chambers. Control of [CO_2] by direct gas injection reduced variability between chambers. Sensor data from the chamber network also demonstrated that it is feasible to use [CO_2] sensors in conjunction with a PID controller to monitor and regulate gas injection volumes to maintain gaseous [CO_2] concentrations. Direct gas injection reduced maximum daily air temperatures in the enclosed headspace environment due to mixing of headspace air with compressed gases held at ambient temperatures. The daily headspace air temperature fluctuations observed within this chamber network were similar to those observed at this time of season under field conditions. Soil temperatures demonstrated significantly more variation between chambers due to different rates of cooling at the soil temperature probe site.

4.2 Introduction

Film use has been proposed as a low-cost means of increasing crop productivity and water use efficiency for broad-acre agricultural and horticultural applications in southern Australia. Film enclosure of the headspace alters environmental conditions beneath the film layer, including solar radiation, temperature and water vapour fluctuations within the enclosed headspace (Chapter 2.4; Olmstead and Tarara, 2001; Orzolek 2017). Film use also increases headspace [CO_2] due to retention of plant and soil microflora emissions (Chapter 2.4.4). Many of these fluctuations are likely to affect seedling development and carbon assimilation by altering leaf size, height and growth rates (Mark & Tevini, 1997), leaf stomatal activity and transpiration rates (Forde *et al.*, 1977; Ray *et al.*, 2002), photosynthetic efficiency and cellular respiration rates (Muchow 1990), and rates of root growth (Hund *et al.*, 2008). Many agricultural species respond to [CO_2] enrichment within the headspace by altering rates of gas assimilation and photosynthesis. Free-air Carbon Dioxide Enrichment (FACE) experiments show that temperate and tropical C_3 crop species (including most cereal, vegetable, tree and ornamental species) show strong responses to [CO_2] enrichment, including increased carbon assimilation and growth rates, reduced stomatal density, activity and transpiration rates, and increased susceptibility to heat stress (Leakey *et al.*, 2009). By contrast, tropical C_4 crops like maize, sorghum and sugarcane under elevated [CO_2] conditions have been less intensively studied, and findings from [CO_2] enrichment studies can be conflicting (Leakey *et al.*, 2006; Kim *et al.*, 2013). Similarly, little is known about the effects of transferring C_3 and C_4 crops from high [CO_2] to lower [CO_2] conditions, which is likely to occur following film removal or *in situ* degradation when film-enclosed crops are exposed to ambient environmental conditions.

To evaluate the accuracy of crop models within film-enclosed environments, it is necessary to be able to monitor the establishment, growth and development of seedlings under film under changing temperatures and [CO_2] levels. Existing models of crop growth and development have been characterised and developed from datasets collected under ambient growing conditions, which may not be representative of seedlings growing within a film-enclosed headspace. For this reason, the assumptions underpinning the photosynthetic and agronomic response models must be evaluated under a film-enclosed headspace.

This chapter describes the design and engineering of a self-recording network of film-enclosed growing chambers that demonstrate the same dynamic environmental processes and mass-energy fluxes described in Chapter 3. To enable [CO_2] to be controlled within pre-set limits, these chambers use direct injections of compressed air and CO_2, regulated by a proportional-integral-differential (PID) controller. The design and development of these chambers are described in this chapter. The chambers replicate the seasonal solar radiation, temperature and vapour pressure fluxes and conditions observed under film, whilst enabling [CO_2] to be maintained within user-defined limits.

4.3 Materials and methods

4.3.1 Greenhouse Chamber Design and Construction

Twelve open-topped greenhouse chambers (620 x 620 x 300 mm) were manufactured (Associated Plastics Tasmania Pty Ltd) from clear 6 mm transparent acrylic polymer (Perspex^{TM}) to enable transmission of solar radiation at low incident angles and minimise solar heating of the chamber material (Figure 4.1). Joints were welded with chloroform, with additional reinforcing provided by internal corner bracing. An additional transparent internal baffle was welded 50 mm in from one edge of the chamber to create a small ante-chamber for the housing and protection of water-sensitive, atmospheric instrumentation. Water and gas pressure drainage holes were installed along the base of the chamber and then overlaid with multiple layers of coarse-woven nursery shade-cloth to enable water drainage while minimising soil loss.

Figure 4.1 Assembled chamber with air-mixing fans, temperature sensors, [CO_2] sensor and data communication module.

Figure 4.2 Wire hoops provide structural support for the polymer film to maintain structure, maximise water runoff and prevent water from rainfall accumulating on the film's upper surface.

The climate instrumentation and associated hardware were co-located within each ante-chamber to prevent electronic componentry being exposed to inclement ambient weather conditions, minimise cable protrusion, and enable the environment to be more effectively sealed. To provide additional protection from contact and corrosion with water condensation, S3101 and S3303 circuit boards were embedded in a polyurethane resin (Resin UR5528, Mektronics Australia, Melbourne, Australia) before being fastened on the inside of the ante-chamber wall and connected to the temperature and CO_2 sensors. Contact points for different voltage circuits (5VDC and 12VDC) were fastened to the wall to provide electricity for the [CO_2] sensor and air-mixing systems, respectively.

Gas injection points were fitted above the soil in each corner of the chamber to enable direct CO_2 and compressed air injection for control of CO_2 concentration. Each chamber was filled with a commercial premium potting substrate to a depth of 25 cm; this left approximately 6 cm of headspace, with the enclosing film supported by steel wires. This additional headspace permitted effective gas mixing and monitoring and replicated the headspace found in double-furrow systems. After filling, a slow-release fertiliser (Osmacote™) and water were added to promote healthy plant growth. Additional support wires were erected over the top of the chamber to support the film canopy and promote the runoff of rainfall (Figure 4.2)

4.3.2 Climate Instrumentation

Non-dispersive infrared (NDIR) waveguide technology sensors (K-30 10,000 ppm sensor, CO_2 Meter Inc., Ormond Beach, FL, USA, Model K30) were installed in a central position to measure [CO_2] concentration, with the gas-permeable film orientated upwards. This placement maximised sensor distance from the sites of air and CO_2 injection, and ensured [CO_2] sensors remained close to moving air currents. These sensors have an operation range of 0-10,000 ppm, with CO_2 concentration linearly correlated with changes in electrical resistance. These changes in resistance are translated into changes in the output voltage of a 5VDC circuit, with sensors transmitting analogue voltage outputs every 2 seconds to the S3101 module (described in Chapter 4.2.4) for measurement and transmission.

Temperature measurements were performed using NTC10K thermistors (SWH-TS-NTC10K temperature sensor, Misol, China) on a 5-volt circuit. Thermistors were embedded in thermally conductive resin for protection against water corrosion and mounted in a protective casing formed from 50 mm reflective polymer tubing to protect from direct radiation, before being filled with thermally conductive resin. This installation process was completed by the thermistor manufacturer prior to purchase. Once assembled, temperatures were monitored by analogue voltage through the thermistor circuit. Conversion of analogue voltages to temperature units was carried out using a B3950 thermistor conversion curve (AVX, Greenville SC, USA). Individual thermistor calibration and standardisation was performed by immersing thermistors in water heated to different temperatures and comparing temperature outputs against thermometer output, generating temperature correction equations for each sensor.

The thermistor sensors were mounted in the instrumentation panel below the soil depth to ensure soil particulate material continuously occluded direct solar radiation from heating the headspace thermistor sensors. Constant headspace air movement and mixing within each chamber was maintained using a 40 mm brushless electric fan (FW-12V DC brushless DC fan, HXS Industrial Co. Ltd., China) mounted adjacent to the headspace temperature sensor in the instrumentation cavity, while an additional three identical fans were suspended on support wires above the chamber growing area.

Identical thermistor temperature sensors were used to monitor soil temperatures in each chamber. These thermistor temperature probes were inserted 5 cm into the soil matrix. Although this monitoring depth is deeper than recommended sowing depths, this depth was found to be required to reliably support the cables protruding from each sensor probe, and to isolate changes in soil temperature from minor fluctuations in the confined headspace air temperature.

4.3.3 Gas Control System

Within each chamber, adjustments to CO_2 concentration were made by direct gas injection. Durations of individual gas injection events were calculated by the PLC using a proportional-integral-derivative (PID) controller function-block algorithm to coordinate compressed gas injection events and calculate injection event volumes. During evaluation, thresholds governing maximum [CO_2] deviations were pre-set at 400 ± 50 ppm. Following calculation, digital signals conveying valve activation and duration signals were transmitted from the PLC to an S3303 digital-to-analogue RS485 communication device (SHJ Electronic, Shanghai, China PRC) for conversion into analogue voltage outputs. Voltage outputs from this device activated a relay (SSR-10 DA, Fotek Controls Co. Ltd, Taiwan) on a 12VDC circuit, enabling the operation of individual gas solenoid valves (Emerson Industrial Automation, Ferguson, MI, USA) from each S3303 output. After activating solenoid valves, compressed gas injections were carried from the gas control system to each recipient greenhouse chamber using 8 mm nylon pneumatic hose and gas fittings installed in the corner of each chamber.

4.3.4 Data communication

Individual S3101 serial communication modules (SHJ Electronic, Shanghai, China PRC) were installed in the instrument cavity space of each chamber to enable the direct measurement of sensor analogue voltage outputs (0-5 VDC) and the conversion and transmission of information into a digital signal. Data collected by each S3101 unit was broadcast to all RS485-enabled devices within the chamber network for collation, storage and use. Transmission of digital serial data throughout the RS485 network was managed by a singular programmable logic controller (PLC) device (Allan-Bradley M820, Rockwell Automation, Milwaukee WI, USA). This PLC coordinated information acquisition and transmission between each S3101 and S3303 device using automated data scanning and [CO_2] response algorithms (Connected Components Workbench, Rockwell Automation, Milwaukee WI, USA). This transmission was performed via RS485 digital serial communication using a MODBUS protocol. Device-specific communication between the PLC unit and each RS485 device was coordinated using device-specific register addresses, enabling data communication to be broadcast selectively or to all units within the system.

Serial data and 24VDC electricity transmission between S3101, S3303 and PLC devices was conducted using a shielded DEKRA-certified multi-core electrical cable (EAS7304P, Electra Cables, Smithfield NSW, Australia) to minimise electromagnetic inductive effects and data loss. All S3101, S3303 and PLC devices were arranged in series to reduce signal reflection. A second shielded multicore DEKRA cable was also installed to transmit electricity for secondary support systems, including a 5VDC circuit to power [CO_2] sensors and a 12VDC circuit to power the electric fans for air mixing. Cable entry and exit points were fitted with nylon waterproof cable glands (OBO Bettermann, Menden, Germany) to prevent water entry and reduce gas and heat loss at the point of cable entry.

Information traffic and CO_2 injection event requests initiated by the PLC were recorded every three seconds by the PLC onto a microSD memory card for storage and access. Information stored on this card was exported as text in a CSV format, then imported and collated into a web-accessible database (APACHE 2.0, Apache Software Foundation, Forest Hill MD, USA). Sensor data from each chamber was averaged over 1hr intervals and temperature sensor data was corrected.

4.3.5 Chamber Performance Testing

System performance tests for inter-chamber temperature uniformity and headspace [CO_2] regulation were carried out during two six-day periods commencing on 30 June and 10 July, 2015 respectively. Tests were carried out at a site in Sandy Bay, Tasmania (42.9°S, 147.3°E), with all statistical analysis carried out using SPSS v22 (IBM, Armonk NY, USA).

In the first testing period, the soil in each chamber was watered to field capacity before being covered with a layer of clear polymer film and monitored for six days. Prior to analysis, recorded soil and headspace temperatures from each chamber were observed to be non-normally distributed, and were log-transformed to improve distribution symmetry. Shapiro-Wilkes normality testing confirmed log-transformed enclosed air and soil data to be normally distributed, after which one-twelfth of the data points for each chamber were subsampled randomly to minimise autocorrelation between observations. This data did not demonstrate increasing variance and met all the requirements for normality, homoskedacity and normal distribution of residuals. Soil temperature and headspace measurements were subsample were subsequently analysed for chamber differences using multivariate analysis of variance (MANOVA), with chamber (CHAMBER) and observation date (DATE) used as independent variables.

In the second testing period, individual chambers were assigned to three different treatment groups: (1) with film, with [CO_2] control via direct gas injection; (2) with film but without [CO_2] control; and (3) no film. Each chamber treatment was spatially replicated four times, with each combination of treatments blocked by location to account for variable localised changes in site microclimate. [CO_2], and soil temperature and headspace temperature data were initially analysed for treatment effects by repeated measures ANOVA. Data were analysed for sphericity using Mauchly's W test prior to analysis, with non-spherical data analysed using a Greenhouse-Geisser adjusted value of epsilon to adjust for departures of sphericity resulting from small dataset size. Where significant film and gas injection treatment and/or block treatment effects were observed, post-hoc analysis effects were performed using Bonferroni-adjusted LSD value to identify significant differences.

4.4 Results

4.4.1 Inter-chamber Temperature Uniformity

Headspace and soil temperatures fluctuated significantly across the observation period due to daily differences in ambient meteorological conditions at the site (Figure 4.3; Figure 4.4). During these diurnal changes, temperatures did not vary significantly between any of the chambers tested ($p = 0.136$), with soil ($p = 0.359$) and headspace air temperatures ($p = 0.097$) remaining similar amongst all chambers. Similarly, individual chambers did not demonstrate interactions with enclosed soil and headspace conditions ($p = 0.799$), with soil ($p = 0.993$) and headspace air ($p = 0.167$) fluxes behaving similarly across all chambers.

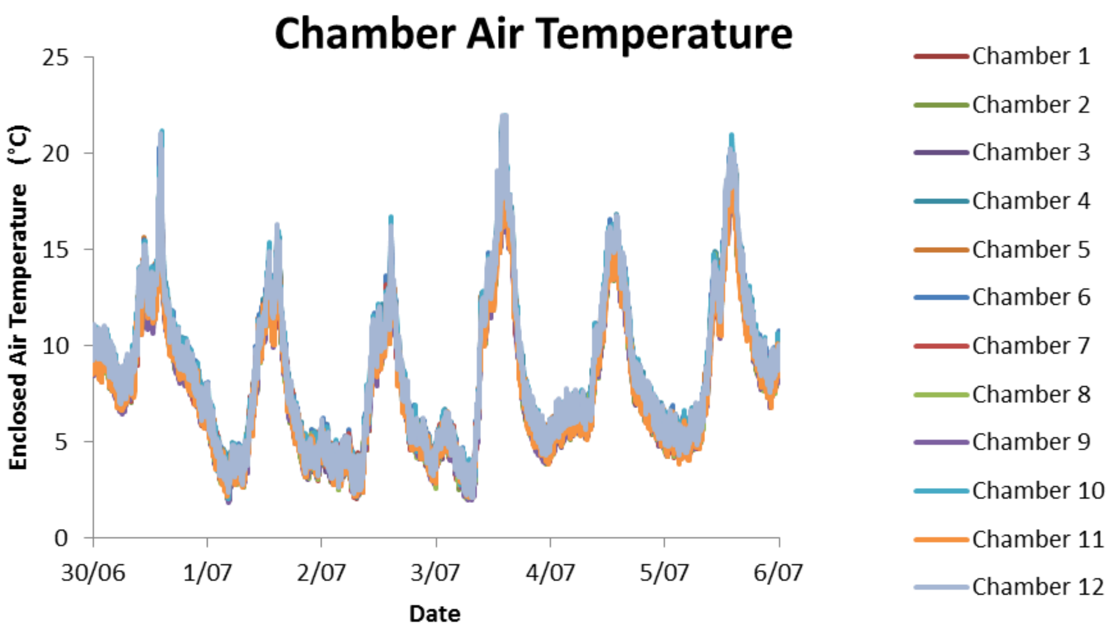


Figure 4.3 Diurnal fluctuations in enclosed headspace air temperatures in 12 chambers during chamber uniformity measurements. During this period, maximum inter-chamber air temperature differences were smallest at low temperatures (2°C) and increased with higher daily temperatures (3°C).

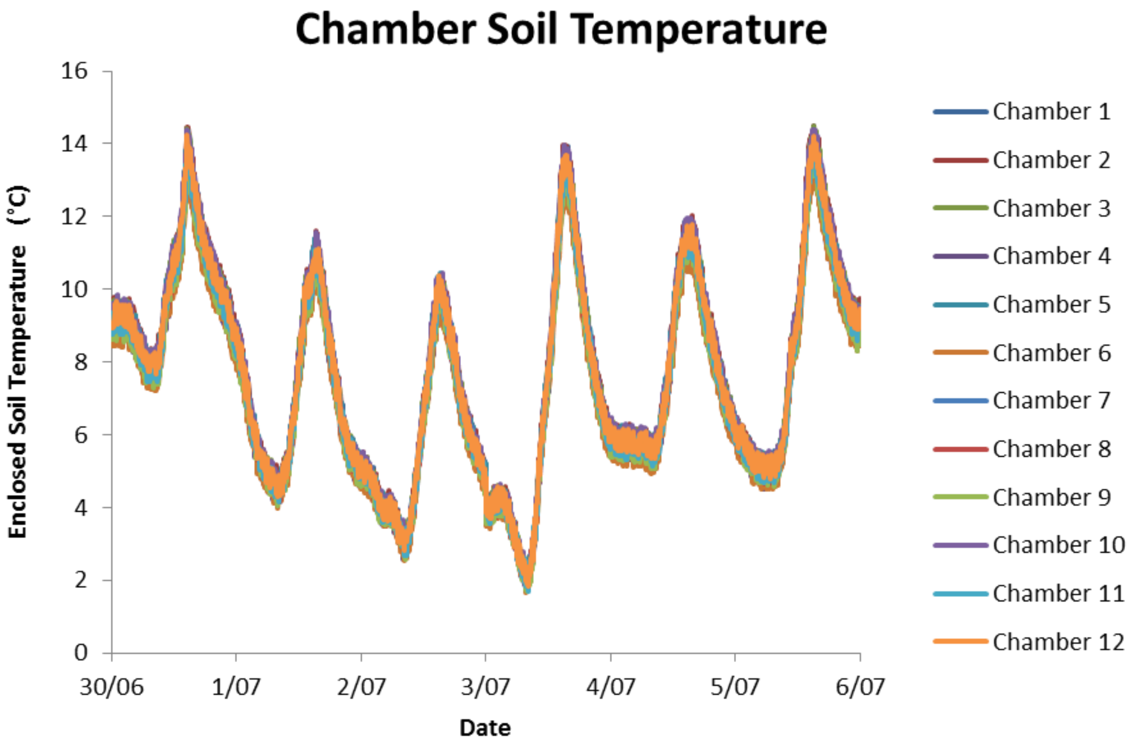


Figure 4.4 Diurnal fluctuations in enclosed soil temperatures in 12 chambers during chamber uniformity measurements. During this period, maximum inter-chamber air temperature differences were smallest at low temperatures (0.6°C) and increased with higher daily temperatures (1.6°C).

4.4.2 Effects of Gas Injection on Headspace Air Temperatures Beneath Film

Diurnal headspace temperature variations interacted differently amongst the film/air treatments tested ($p = 0.030$). Above-ambient increases in enclosed headspace air temperatures were also greater when the CO_2 was unregulated, increasing by approximately 0.07°C per degree ambient temperature (Figure 4.5). Headspace air temperatures under the film were greater than the control (Figure 4.6).

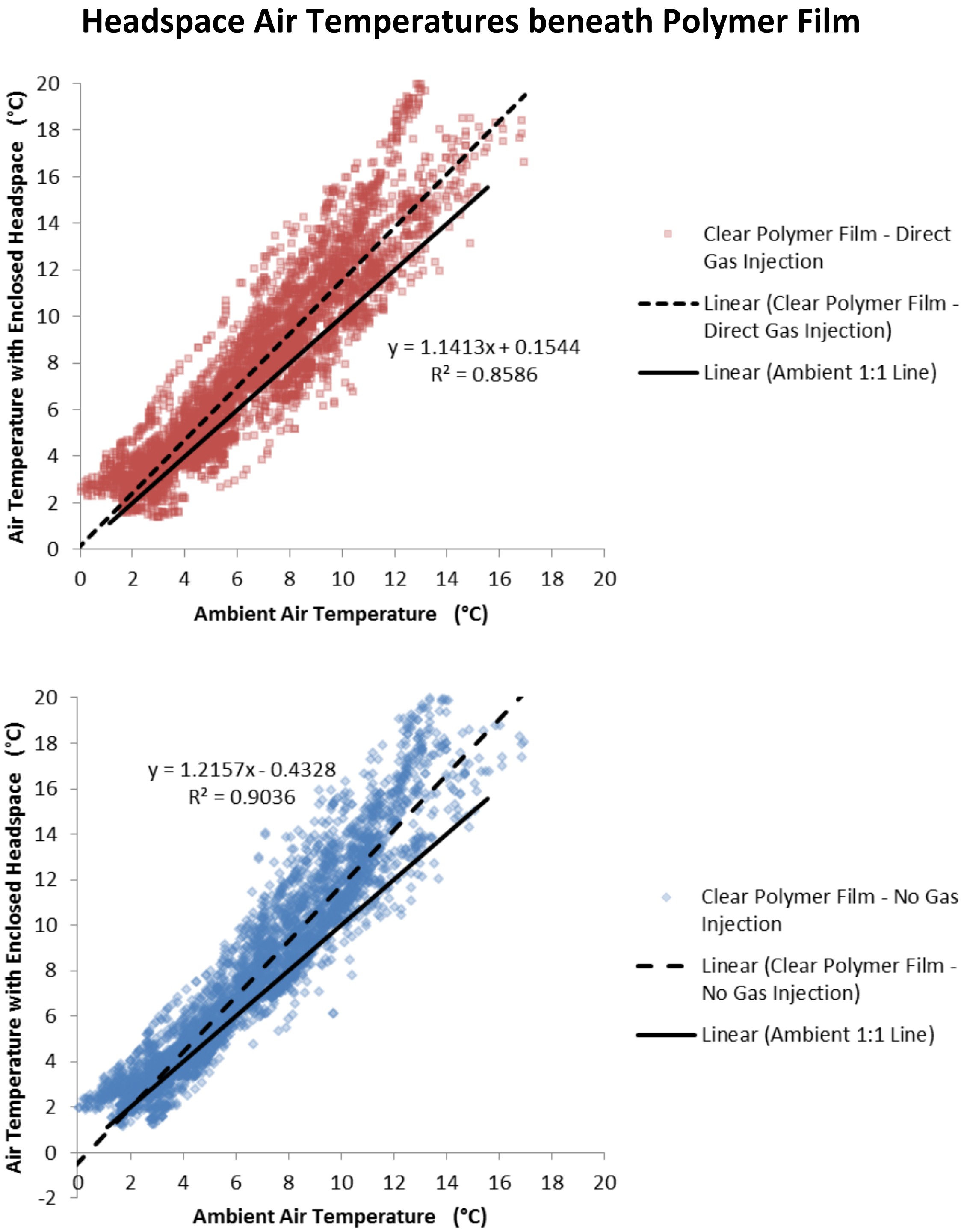


Figure 4.5 Headspace air temperatures observed within all chambers (a) utilising direct gas injection for [CO_2] control, and (b) without any form of [CO_2] controls.

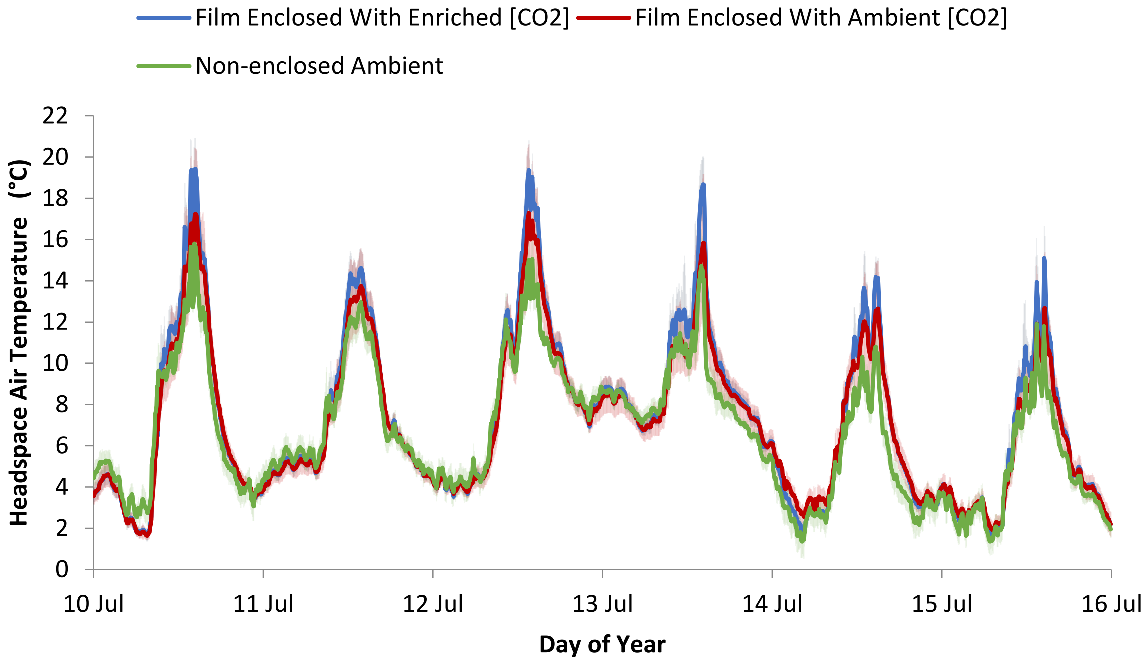


Figure 4.6 Air temperature treatment means and variability for each treatment. Standard errors for each treatment are displayed in the shaded area.

4.4.3 Effects of Gas Injection on Soil Temperatures Beneath Film

Diurnal soil temperature fluctuations interacted with the film-gas treatments applied throughout the monitoring period ($p = 0.040$). Soil temperature increased to similar levels under film regardless of whether the air was mixed, or not; however subsequent cooling events at night occurred much more slowly in the treatment receiving direct gas injections for [CO_2] control (Figure 4.7). Maximum daily soil temperatures were also greater in both polymer-film enclosed treatments than in the non-enclosed control treatment.

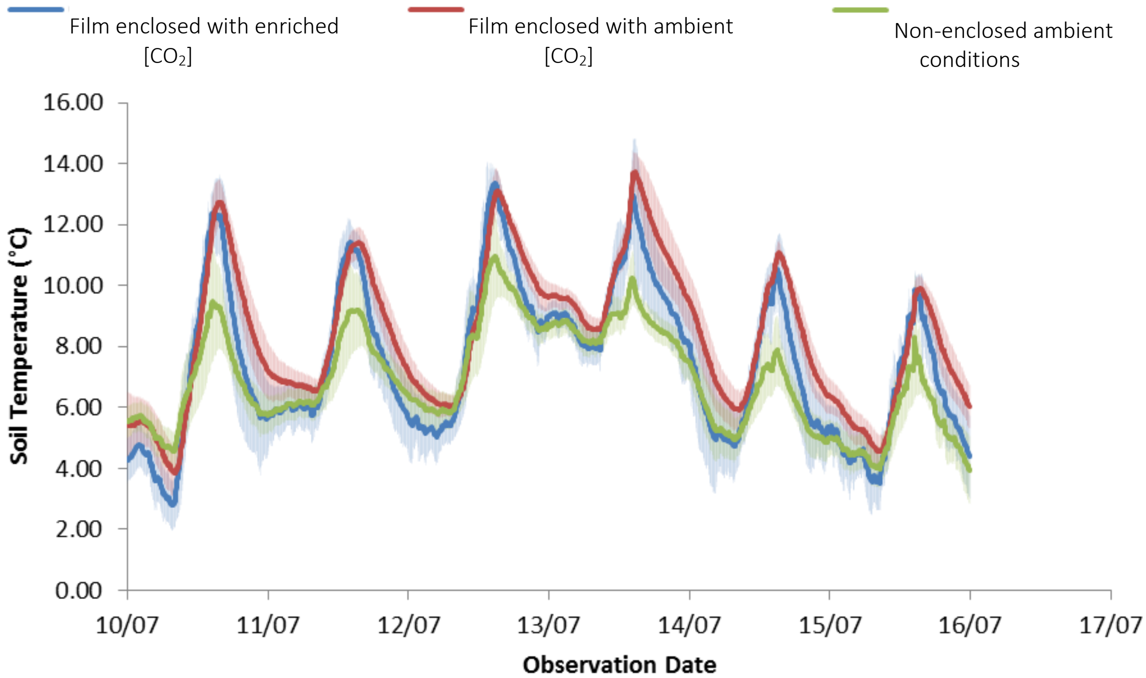


Figure 4.7 Soil temperature treatment means and variability. Standard errors of the mean for each treatment are displayed in the shaded area

4.4.4 Efficacy of [CO_2] Control Under Film

Mean [CO_2] varied significantly across the replicates throughout the testing period ($p = 0.020$), but did not interact significantly with treatments ($p = 0.504$). Throughout the six-day observation period no differences in mean [CO_2] were observed ($p = 0.356$), with CO_2 fluctuations across all treatments remaining within the 350-450 ppm [CO_2] thresholds (Figure 4.8). Despite this, chambers with film and the direct gas injection (DGI) system for [CO_2] correction demonstrated increased diurnal uniformity and reduced inter-chamber variability compared to chambers with film but no [CO_2] control.

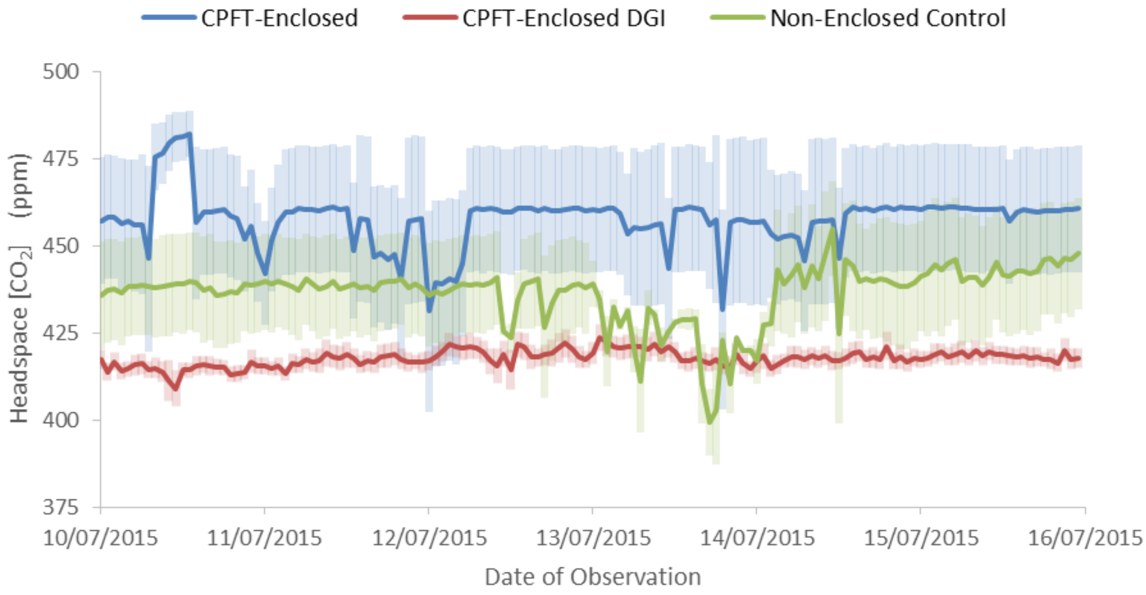


Figure 4.8 Mean CO_2 concentrations in each treatment group. Shaded areas represent standard error of the mean.

4.5 Discussion

The daily headspace air temperature fluctuations observed in this chamber network were similar to those observed at this time of season under field conditions in Chapter 2.4 (Lisson *et al.*, 2016). Under identical film treatments, each of the 12 chambers displayed similar soil and headspace air temperature profiles (Figure 4.3; Figure 4.4; Figure 4.6). This similarity indicates that significant temperature changes between polymer film or headspace gas composition reflect real changes in the physical drivers regulating temperature accumulation and loss within the enclosed environment.

Sensor data from the chamber network also demonstrated that it is feasible to use [CO_2] sensors in conjunction with a PID controller to monitor and regulate gas injection volumes to maintain gaseous [CO_2] concentrations. Figure 4.5 demonstrates that chambers utilising regulated direct gas injections to regulate headspace [CO_2] maintained greater stability and reduced inter-chamber variability. This success provides a mechanism for the growing of plants under different headspace [CO_2] treatments despite fluctuating temperature conditions. Within the non-[CO_2]-controlled chambers enclosed by film, diurnal [CO_2] fluctuations beneath clear polymer film were smaller in magnitude than those previously observed in field observations under warmer seasonal conditions (Lisson *et al.*, 2016). Part of this reduction in diurnal [CO_2] fluctuations may reflect seasonal temperature-related limitations to cellular respiration rates in soil-borne organisms (Atkin and Tjoelker, 2003; Lloyd and Taylor, 1994). Mean [CO_2] at the soil surface was also observed to vary by almost 40 ppm between [CO_2]-controlled and [CO_2] non-controlled treatments. Due to the temporal stability and consistency of both treatments, it is most likely that this discrepancy is an unanticipated artefact arising from using published meteorological observations of atmospheric [CO_2], rather than measurements taken from the soil surface. As such, it is advised that future efforts at controlling headspace [CO_2] by direct gas injection use a slightly higher (~460 ppm) mean [CO_2] baseline to account for soil [CO_2] emission effects.

In this experiment it was noted that direct gas injection reduced solar heating efficiency and maximum daily air temperatures by 2 - 3°C (Figure 4.6) within the enclosed headspace environment due to the mixing of headspace air with compressed gases held at ambient temperatures. Differences between regression coefficients outlined in Figure 4.6 suggest that temperature variations between [CO_2]-controlled and non-controlled treatments are small during daily periods where there is little difference in enclosed and ambient air temperatures but may increase significantly during periods of high solar radiation intensity. Under these conditions, temperature dilution effects may be magnified, creating significant temperature differences between [CO_2]-controlled and non-controlled film-enclosed environments. Under these conditions, it may be advisable to insulate all gas injection lines and install in-line heating elements in the injection system to enable differences in headspace and ambient air temperatures to be corrected prior to gas injection.

Soil temperatures demonstrated significantly more variation between chambers due to different rates of cooling at the soil temperature probe site. Some of this variation was caused by the presence of a lateral temperature gradient between the north/sun-facing chamber walls and the temperature probe. These temperature fluxes are opposite in magnitude to lateral temperature fluxes observed by Mahrer (1979) using clear polymer film row covers under field conditions. This reversal of temperature fluxes reflects the increased solar radiation transmission to the soil per unit of area at the soil surface, as well as thermal isolation of each chamber from its surrounding environment, thereby reducing lateral and total thermal conduction and heat diffusion capacity of soil in the isolated chambers. Elimination of this lateral temperature gradient may be feasible by coating the chamber with a highly reflective material. This was not undertaken in this experiment, due to potential interference from reflected radiation as a result of the close proximity of the chambers to each other.

4.6 Conclusion

In this study results from the development and testing of a low-cost network of computer-controlled greenhouse chambers were presented showing that they are capable of emulating natural temperature fluctuations observed beneath clear polymer film in southern Australia whilst controlling and stabilising [CO_2] concentrations. In the following chapter, this chamber network will be used to enable maize to be grown beneath film under controlled concentrations of CO_2, allowing repeated measurement and quantification of film effects on maize agronomic and photosynthetic characteristics.

Chapter 5: Physiological Effects of Film Use in Maize

5.1 Abstract

Film is used in many cool-climate production regions to protect against seasonal frost, promote faster crop establishment and early growth, reach key phenological development milestones earlier, and extend the growing season. Biophysical modelling has indicated that film use in Tasmania would create maximum daily temperature conditions which are too warm for temperate cereals like wheat, oats and barley, but which would be suitable for the production of tropical cereal crops like maize and sorghum. One strategy for reducing the incidence of heat stress would be to sow earlier than the recommended in the current regional planting windows. For that strategy to be successful, these crops would have to be able to adjust to the rapidly changing temperature and [CO_2] conditions present under film, and to survive cold overnight temperatures and chilling exposure.

Film use had significant beneficial effects on seedling emergence, leaf and biomass production rates, increased seedling leaf CO_2 assimilation rates, and reduced leaf stomatal conductance during the period of film use. Film use also enabled seedlings to maintain higher concentrations of leaf chlorophyll, reduced leaf baseline fluorescence (F_0) and increased leaf maximal fluorescence, enabling greater utilisation of incident solar radiation, except during periods of acute heat stress. Headspace [CO_2] had minimal influence on seedling photosynthetic physiology and agronomic development. These findings suggest that film use can improve seedling establishment, agronomic development and the photosynthetic physiology of maize growing under cold seasonal conditions.

5.2 Introduction

Film is used in many cool-climate production regions to protect against seasonal frost, promote faster crop establishment and early growth, reach key development milestones and extend the growing season (Kwabiah 2002; Crowley 1997; Easson and Fearnehough 2000, FAO 2008). When used for this purpose, film use increases soil and headspace temperature and [CO_2] (Carter 2008, Lisson *et al.*, 2015), reduces water losses from evapotranspiration and reduces crop consumption of irrigation water (Braunack *et al.* 2015). The higher temperatures present beneath film enable earlier sowing dates, reduce early-season cold stress, encourage leaf area production for solar radiation interception, and enable faster thermal time accumulation and phenological development (Walker, 1969). The subsequent advancement of flowering and crop maturation may also reduce late-season frost risk.

Biophysical modelling has shown that film use will create maximum daily temperature conditions which are too warm for temperate cereals like wheat, oats and barley, but which are suitable for the production of tropical C_4 cereal crops like maize and sorghum (Chapter 3). Production of these tropical cereals is currently limited in Tasmania due to frost and cold stress (Rawnsley *et al.*, 2007; Pembleton and Rawnsley, 2012). Use of film has already been successfully incorporated into maize grain, silage and sweet corn production systems in cold-constrained regions of France (Ballif and Dutil 1974), England (Phipps 1994), Scotland (Hameleers 1997), Ireland (Keane 1996, Keane 1997, Crowley 1996), Canada (Kwabiah 2002, Kwabiah 2004), the USA (Adams 1970) and northern Japan (Nakui *et al.,* 1995).

High head space temperature has been identified as a major constraint on film use in Tasmania (see Chapter 3.4.4). Daily head space temperatures in excess of 32 °C were first observed during early September and increased in frequency, severity and duration in response to rapid seasonal changes in day length, solar energy intensity, ambient air temperatures and reductions in cloud cover density (Miller and Bunger, 1968).

One strategy for reducing the incidence of heat stress during seedling growth is to bring forward regional planting dates. Once the film breaks down (typically 30-50 days after sowing) the crop continues to grow normally without risk of film-induced heat stress. Successful production of film-enclosed tropical C_4 cereals in Tasmania is dependent on crops being able to adjust to the rapidly changing temperature and [CO_2] conditions present under film, and to survive cold overnight temperatures and chilling exposure. At a whole-of-plant level, chilling stress slows coleoptile growth, root development (Richner *et al.,* 1996), leaf initiation (Walker 1969; Tollenaar *et al.,* 1979; Warrington and Kanemasu 1983), leaf tissue cell division, elongation and expansion (Ben-Haj-Salah and Tardieu 1995), and shoot elongation (Duncan and Hesketh 1968). Cold stress also promotes cell and tissue injury, reduces rates of metabolic activity, cell division and elongation, and causes germination, radical growth and seedling emergence to occur slowly and erratically (Miedema 1982; Miedema *et al.,* 1987; Imholte and Carter 1987). These effects decrease seedling survival and emergence when soil temperatures are below 10-12°C (Benjamin 1990; Nafziger 2003, Steward 1990).

Previous agronomic studies of film-enclosed silage maize growth in cold-climate regions have demonstrated increased maize grain yield, quality and DM content when plants were initially established beneath film in temperature-limited regions (Hanras 1979; Van der Werf 1993; Crowley 1998; Easson and Fearnehough 2000). Unfortunately, previous studies into the effects of film use have not recorded temperatures in the film environment and have focused exclusively on parameters measured at the time of harvest, long after the film material has been removed or structurally degraded *in situ* (Kwabiah 2003; Crowley 1998; Easson and Fearnehough 2000; Hopen 1965; Free and Bay 1965; Bible 1972; Kretschmer 1979; Mansour 1984; Felcyznksi 1994; Aguyoh *et al.,* 1999; Hanras 1979; Van der Werf 1993; Crowley 1998; Easson and Fearnehough 2000). To date, little distinction has been made between intact (non-perforated) and perforated films, of which the latter would be expected to reduce [CO_2] entrapment and increase air convection, heat loss and soil moisture loss.

For these reasons, the physiological, agronomic and emergence effects of film use on maize seedlings is undocumented and unknown, and it is uncertain how long the benefits of film use may persist after film breakdown or removal. To address these gaps in the literature, this chapter will explore the agronomic and photosynthetic characteristics of maize grown as a model tropical cereal crop in a film-enclosed growing environment, and how these parameters are influenced by rapid daily fluctuations in headspace temperatures, solar radiation intensity, and [CO_2].

5.3 Materials and Methods

5.3.1 Experiment Design

Three treatment groups were used in this experiment, which was conducted between July and November 2015 at the University of Tasmania Sandy Bay campus (42.9°S, 147.3°E). The experiment was conducted using the [CO_2]-controlled chambers described in Chapter 4, which were set up outdoors under ambient light and temperature conditions. Treatment groups used in this experiment were (a) seedlings grown under film with increased temperature and [CO_2] conditions, (b) seedlings grown under film with increased temperatures but ambient [CO_2] conditions, and (c) seedlings grown without film under ambient light, temperature and [CO_2] conditions.

Throughout this experiment, plants growing in treatment groups (a) and (b) were grown beneath film for 93 days, during which they were monitored regularly for ontogenic development and photosynthetic physiology (see below). Film covers were kept at a fixed height of approximately 50mm above soil surface, replicating headspace size created in enclosed double furrow systems in the northern hemisphere. Film was removed from these treatments 93 days after sowing (DAS), causing seedlings to acclimate to new ambient temperature and [CO_2] conditions. During this adjustment period, all seedlings continued to be monitored for ontogenic development and photosynthetic physiology to identify changes in these processes caused by film removal.

Comparisons between treatment groups (a) and (b) were used to assess the agronomic and photosynthetic physiological effects of headspace [CO_2] on seedlings growing under film. Comparisons between treatment groups (b) and (c) were used to assess the effects of concomitant changes in headspace temperature and solar radiation intensity caused by film use. Comparisons were also made between seedlings during and after film use to identify changes in photosynthetic physiology caused by film removal.

5.3.2 Chamber Preparation

Chambers were filled with a premium commercial potting mix and 100g slow release fertiliser (Osmacote, Scotts Australia, Belle Vista NSW, Australia). Individual chambers were randomly allocated one of three treatments: non-enclosed ambient [CO_2] (~400 ppm), film-enclosed with ambient atmospheric [CO_2] (400ppm), and film-enclosed with naturally elevated [CO_2] (>2000 ppm). Chamber treatments were replicated four times and blocked by location. Film headspace height remained fixed for the duration of the experiment.

5.3.3 Planting Date Selection

To minimize the chances of heat stress and crop failure as plants grew into warmer spring temperatures, the sowing date used in this experiment was brought forward to 16 July (0 DAS) . This allowed the film-enclosed plants to make optimal use of cooler temperatures during winter and early spring. During sowing, 150 evenly spaced kernels of maize (Pioneer hybrid cultivar P9400, Pioneer Australia, Australia) were planted at a depth of 2.5cm, watered to field capacity.

5.3.4 Emergence & Establishment

The number of newly emerged seedlings in each chamber was monitored daily until 55 days after sowing (DAS). The plant population in each chamber was counted and thinned at 70 DAS to determine total number of emerged seedlings (ESTABLISHMENT). After total establishment had been determined, rates of daily seedling emergence were divided by total number of established seedlings (EMERGENCE) to remove any confounding effects caused by seed age and quality.

Analysis of film treatment effects (Film + CO_2, Film – CO_2, ambient control) was performed using R Studio v0.99.903 (R Studio, Boston, MA, USA). Rates of seedling emergence were analysed by logistic regression. Seedling establishment at 70 DAS was assessed using a one-factor analysis of variance (ANOVA), with significant treatment differences identified using Tukey's Honest Significant Difference (HSD) method. Due to seedling destructive sampling requirements, seedling biomass accumulation and leaf area were analysed using multivariate analysis of variance (MANOVA), with significant treatment differences identified using Tukey's HSD.

5.3.5 Seedling Development

The plant population in each chamber was assessed for visible health and development. Daily thermal time was calculated using the cardinal temperature values presented in described in Chapter 3.3.4, using the cardinal temperature values presented in Table 3.1.

Each chamber was thinned to 14 uniform plants per chamber at 70 DAS. Three plants were sampled at the four- and five-leaf stages (GS14 and GS15) to determine biomass production and leaf area per plant across all treatments. Leaf area was measured by physical paper weight after each leaf was segmented, photocopied and the entire leaf area excised. Paper density and mass were used to determine paper area, with paper thickness assumed to be constant.

5.3.6 Leaf Chlorophyll and [CO_2] Exchange

The most fully expanded leaves of eight randomly selected plants were assessed for leaf relative chlorophyll content (RCC) using a SPAD chlorophyll meter (Apogee Instruments, Logan UT, USA). Seedling RCC were analysed using repeated measures ANOVA, with significant film treatment effects identified using Tukey's HSD.

Following chlorophyll measurement, a Li-Cor 6400XT infrared gas analyser (IRGA) (LI-COR Biosciences, Lincoln NE) was used to determine leaf CO_2 assimilation rates (A) and transpiration (E) from two randomly selected plants every three days. Prior to $[CO_2]$ assimilation measurements, plants were allowed to acclimate to full sunlight for at least one hour before measurement. These measurements were taken from the midpoint of the most recently fully expanded leaf of each plant under saturated PAR conditions (A_{sat}) (Evans and Santiago, 2014). During these measurements, $[CO_2]$ in the leaf chamber was maintained at 390 μmol.mol^{-1}, and photosynthetically active radiation (PAR) at 1500 μmol.m^{2}.s^{-1}. Measurement of leaf photosynthetic responses to light were also recorded at two intervals, with recordings taken at 20°C and $[CO_2]$ of 390 μmol.L^{-1}. PAR was varied between 0 and 2000 μmol m^{-2} s^{-1} at the following intervals: 1500, 2000, 1500, 1000, 650, 300, 200, 100, 50, and 0 μmol photons.m^{-2} s^{-1}. Photosynthetic responses to changes in $[CO_2]$ (A:Ci) were also monitored at two intervals, at 20°C and photon flux density of 1500 μmol photons.m^{-2} s^{-1}. $[CO_2]$ was varied between 0 and 1750 mmol L^{-1} using the following sequence: 390, 300, 200, 150, 100, <50, 390 450, 600, 800, 1000, 1500, and 1750 μmol.L^{-1} respectively. During all measurements the IRGA flow rate was maintained at 390 μmol.s^{-1}, and leaf temperature was maintained at 20°C.

The effects of film use and headspace $[CO_2]$ upon transpiration rate (g) were derived using the multivariate approach of Collatz *et al.*, (1991). This approach enabled identification of linear response to photon flux density (g_1), and changes to the light compensation point for stomatal activity (g_0). Analysis of film treatment effects (Film + CO_2, Film – CO2, ambient control) was performed using R Studio v0.99.903 (R Studio, Boston, MA, USA). Non-rectangular hyperbolic response curves were fitted to A:C_i and PAR $[CO_2]$ assimilation observations using the *Plantecophys* package (Duursma 2015) to estimate physiological model parameters for transpiration (g_0, g_1) for seedling populations growing within each chamber. Values for these parameters were subsequently analysed for pre- and post-film removal treatment effects using multivariate ANOVA, with significant treatment effects identified using Tukey's HSD.

The effects of film use and headspace $[CO_2]$ upon $[CO_2]$ assimilation rates were derived using the multivariate approach of von Caemmerer (2000). This approach enabled identification of linear response to photon flux density (g_1), and changes to the light compensation point for stomatal activity (g_0). Analysis of film treatment effects (Film + CO_2, Film – CO_2, ambient control) was performed using R Studio v0.99.903 (R Studio, Boston, MA, USA). Non-rectangular hyperbolic response curves were fitted to A:C_i and PAR [CO_2] assimilation observations using the Plantecophys package (Duursma 2015) to estimate physiological model parameters from [CO_2] assimilation for seedling populations growing within each chamber. These parameters included the maximum rate of Rubisco activity (Vc_{max}) and Michaelis-Menten coefficient (K_m) for Rubisco kinetics, the photosynthetic CO_2 compensation point (Γ*), and the of electron transport (J_{max}) and dark respiration (R_d). Values for these parameters were subsequently analysed for pre- and post-film removal treatment effects using multivariate ANOVA, with significant treatment effects identified using Tukey's HSD.

5.3.7 Leaf Fluorometry

Three recently fully expanded leaves were randomly selected and measured for PSII function and efficiency by Phase Amplitude Modulated (PAM) fluorometry (OS-30 chlorophyll fluorometer, Opti Sciences, Hudson NH, USA) under prolonged dark conditions every two days (Blackmer and Schepers, 1995; Chapman and Barreto, 1997). Following film removal, fluorometric measurements were collected every two days for 10 days to monitor acclimation response; after this period, long-term measurements were collected every five days for another 20 days. Chlorophyll baseline fluorescence (F_0), PAR receptor density (F_m) and photochemical quenching proportion (q_P) were also analysed by repeated measures ANOVA using a fully factorial design, with film treatment effects identified using Tukey's HSD.

5.4 Results

5.4.1 Film Temperature Effects

The effect of film on heating and cooling processes altered the daily temperature profile of the crop-growing environment. Daily temperature fluctuations from solar heating occurred rapidly within the film-enclosed treatment, elevating maximum headspace temperatures by 5-15°C above ambient temperatures over the duration of the experiment. Over the winter/spring period headspace temperatures were within the 14-23 °C exponential growth response (Walker 1969) and/or 23-32 °C physiologically optimal (Mahan *et al.,* 1990) temperature ranges for maize growth and development (Figure 5.1). Without the protection of this insulating layer of film, headspace temperatures in the growing environment were much lower than when enclosed by film throughout the observation period, and on many days temperatures did not exceed minimum cardinal temperatures required for leaf elongation (7.3 ± 3.0 °C), stem growth (10.9 ± 1.4 °C) and/or root growth (12.6 ± 1.5 °C), as described by Sánchez *et al.* (2014).

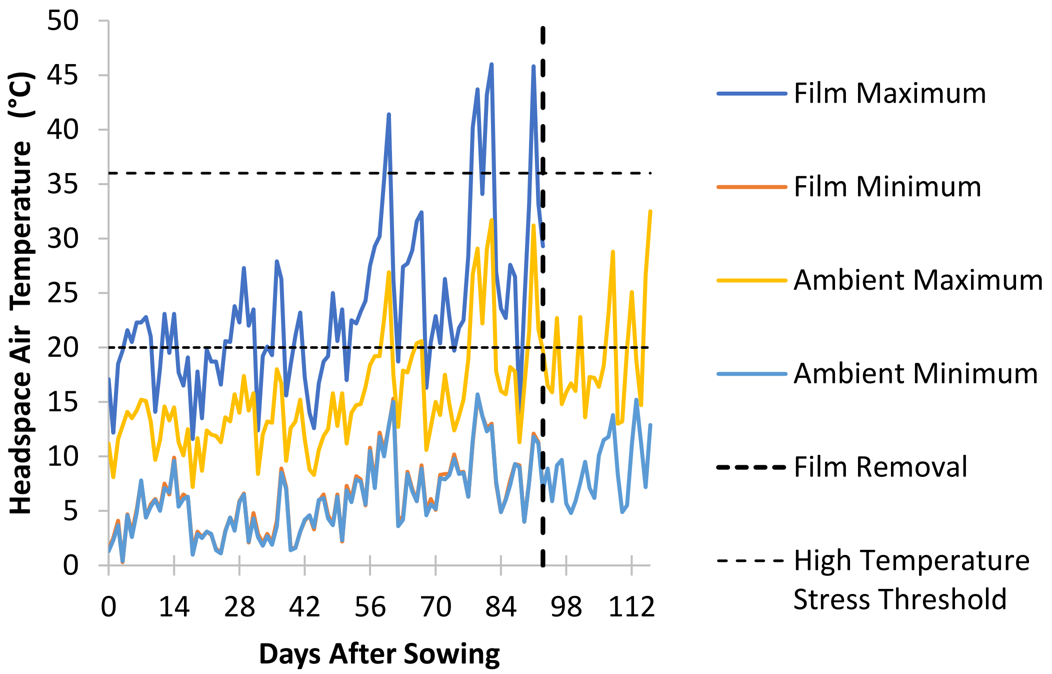


Figure 5.1 Maximum and minimum daily air temperatures within enclosed headspace and ambient air temperatures between 0 and 114 DAS (16 July - 9 November 2015).

5.4.2 Emergence and Establishment

Film enclosure had significant beneficial effects on early-sown seed emergence and stand establishment ($p < 0.001$). Seed establishment was high in both film-enclosed treatments, with less than 10% of planted seeds failing to emerge during the experiment. Much of this emergence occurred 28-44 days after sowing (Figure 5.2), with 93.0% of seeds emerging within 52 days of sowing. By contrast, emergence rates of early-sown seed were low in the non-enclosed control treatment, with only 10% of planted seedlings emerging within 52 days of sowing (Figure 5.2). Establishment rates were low in the non-enclosed control, with 58% of sown seed completing emergence within 70 days of sowing (Figure 5.3). No differences were observed in seed establishment or daily emergence rates in film-enclosed treatments in response to changes in headspace [CO_2].

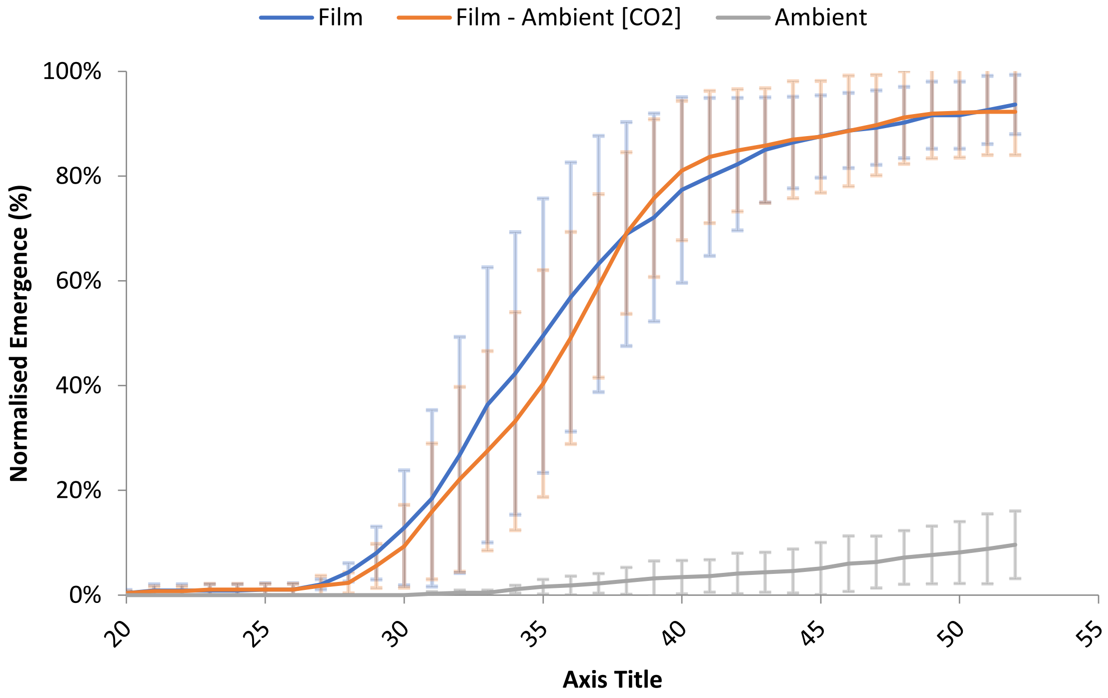


Figure 5.2 Effect of film on seedling emergence. Values represent mean emergence ± SEM.

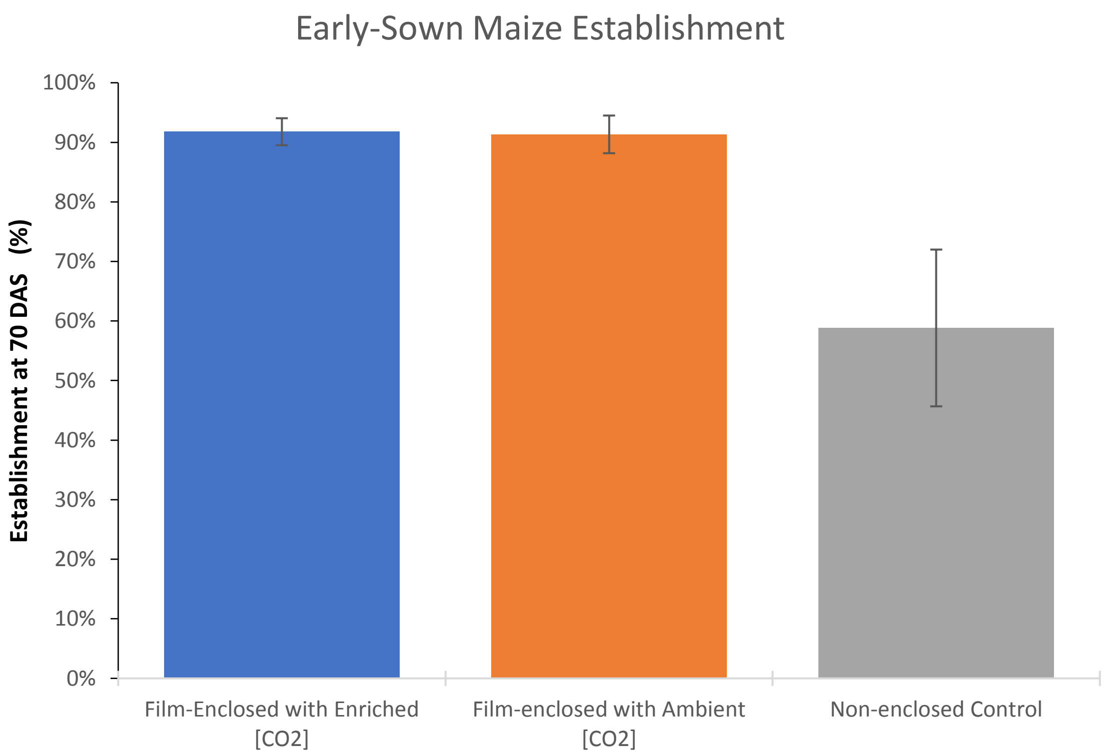


Figure 5.3 Mean establishment of early-sown maize seedlings 70 days after sowing. Bars represent the SEM.

5.4.3 Thermal Time Accumulation & Seedling Development

Film use increased rates of thermal time exposure by approximately 30% above ambient conditions (Figure 5.4a). Mean daily thermal time accumulation varied between significantly seedlings growing under film-enclosed and ambient conditions, but cumulative thermal time exposure between film-enclosed treatments were minimal. Increases in temperature and thermal time accumulation were associated with increased leaf area ($[CO_2]$-enriched $p_{adj} < 0.001$; $[CO_2]$-ambient $p_{adj} < 0.001$; Figure 5.5a) but differences in leaf area between film treatments using naturally enriched and ambient $[CO_2]$ were not significant ($p_{adj} = 0.893$), and no interactions were observed between treatment and DAS ($p = 0.085$).

Mean seedling biomass was also higher within film-enclosed treatments when compared with the non-enclosed control treatment ($[CO_2]$-enriched $p_{adj} < 0.001$; $[CO_2]$-ambient $p_{adj} < 0.001$; Figure 5.5b), but differences in biomass between film treatments using enriched and ambient $[CO_2]$ were not significant ($p_{adj} = 0.867$).

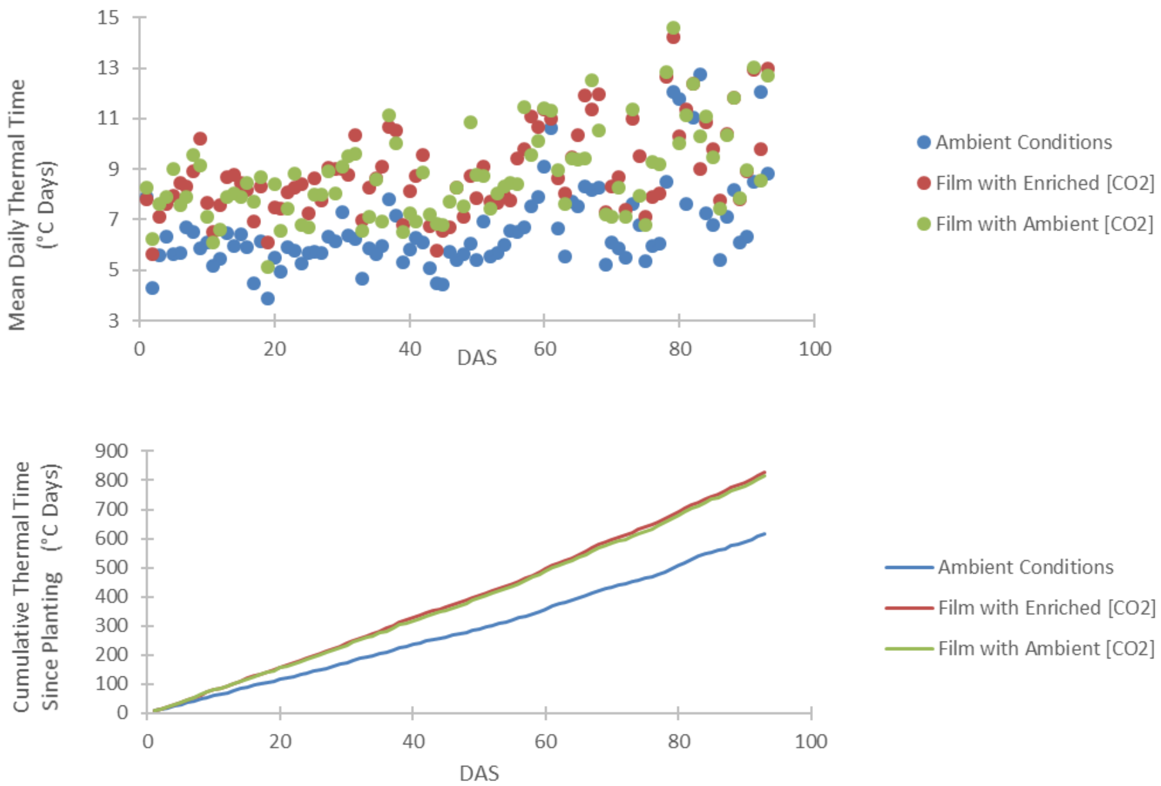


Figure 5.4 Daily (A) and cumulative (B) thermal time exposure of early-sown maize seedlings grown under ambient conditions (grey) and beneath film (coloured).

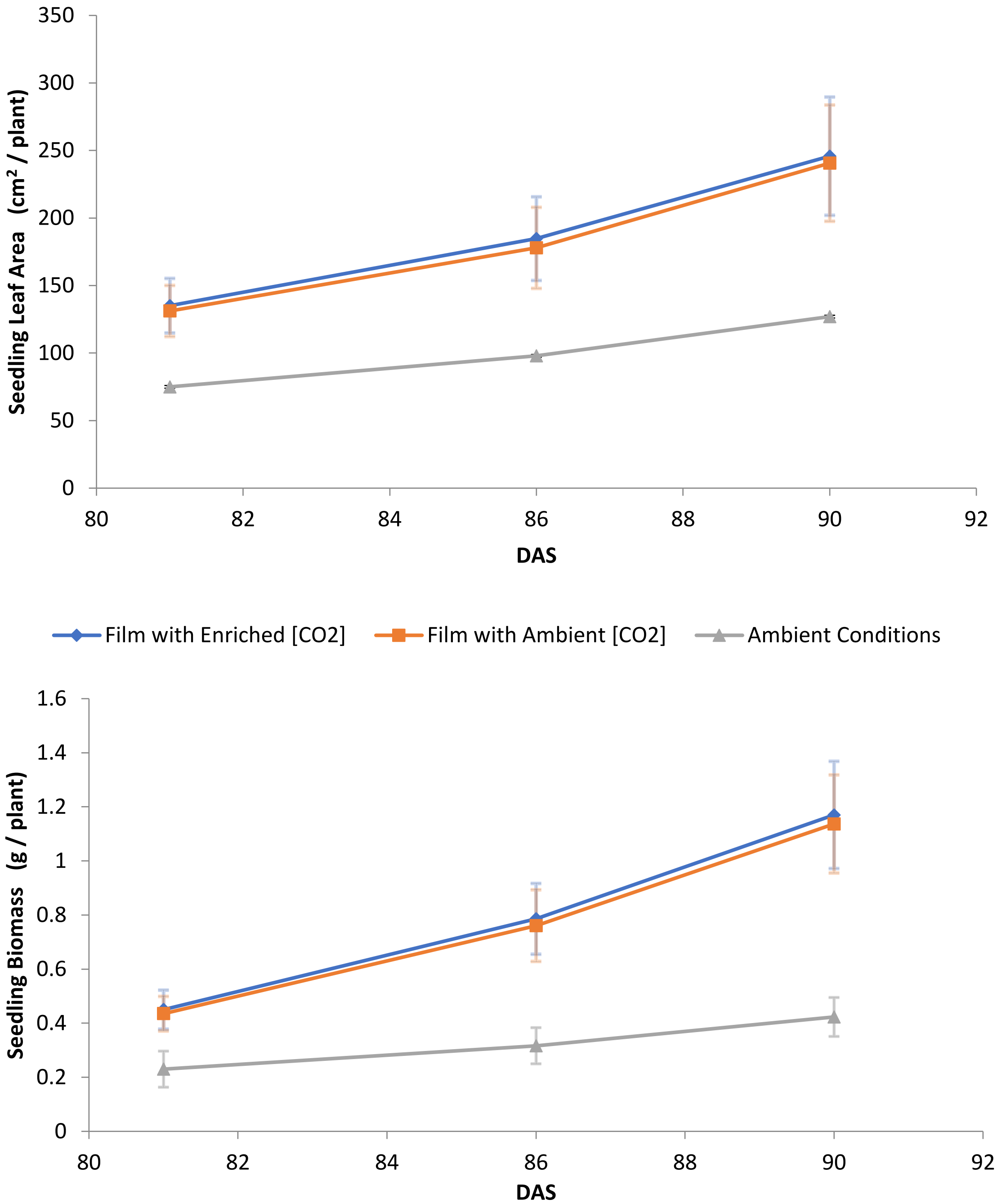


Figure 5.5 Mean total leaf area (A) and above-ground biomass production (B) per plant in early-sown seedlings post-thinning. Bars represent the SEM.

5.4.4 Gas Exchange

Film use reduced leaf stomatal conductance (g) of early-sown maize seedlings during the period of film use (Table 5.1). When analysed using the multivariate approach of Collatz *et al.* (1991), film use decreased the linear response coefficient of stomatal activity (g_1) ($p = 0.005$), but this change did not persist following film removal ($p = 0.066$) (Table 5.1). The light compensation point for stomatal activity (g_0) increased across all treatment groups (including the control group) during the period of film removal but did not influence ($p = 0.287$) or interact with film use or headspace [CO_2] enrichment ($p = 0.093$). Headspace [CO_2] did not influence g_0 or g_1 during film use, indicating that maize seedling stomatal conductance is not influenced by the passive headspace [CO_2] enrichment normally associated with film use (Table 5.1).

Leaf assimilation of CO_2 also increased during periods of film use (Table 5.2; Figure 5.6; Figure 5,7). Prior to film removal, rates of leaf CO_2 assimilation under PAR-saturated conditions (A_{sat}) were significantly higher in film-enclosed treatments when compared to the control treatments grown under ambient temperature and ambient [CO_2]. Film-treatment interactions were observed to influence the maximum rate of Rubisco activity (Vc_{max}) ($p = 0.036$), the photosynthetic CO_2 compensation point (Γ^*) ($p = 0.031$), and the Michaelis-Menten coefficient (K_m) for Rubisco kinetics ($p = 0.029$) of early-sown seedlings growing under film. Use of film was not observed to interact with rates of electron transport (J_{max}) ($p = 0.080$) or dark respiration (R_d) ($p = 0.080$).

Table 5.1 Stomatal conductance parameters of maize seedlings at different PAR photon density when grown under an enriched [CO_2] film-enclosed environment, an ambient [CO_2] film-enclosed environment, and a non-enclosed environment. Numerical values represent treatment mean value and standard deviations.

Film Treatment	Light compensation point for Stomatal Activity (g_0) (µmol m^{-2} s^{-1})	Linear slope coefficient of stomatal activity (g_1) (µmol m^{-2} s^{-1})
Film with enriched [CO_2]		
Pre-removal	0.060 ± 0.034	0.328 ± 0.340
Post-removal	0.091 ± 0.025	0.793 ± 0.220
Film with ambient [CO_2]		
Pre-removal	0.059 ± 0.006	0.203 ± 0.426
Post-removal	0.112 ± 0.024	0.602 ± 0.255
Non-enclosed control		
Pre-removal	0.051 ± 0.020	1.245 ± 0.297
Post-removal	0.141 ± 0.005	0.886 ± 0.311
Significance (p value)		
Treatment	0.287	0.005
Film Presence	<0.001	0.271
Treatment*Film Presence	0.093	0.066

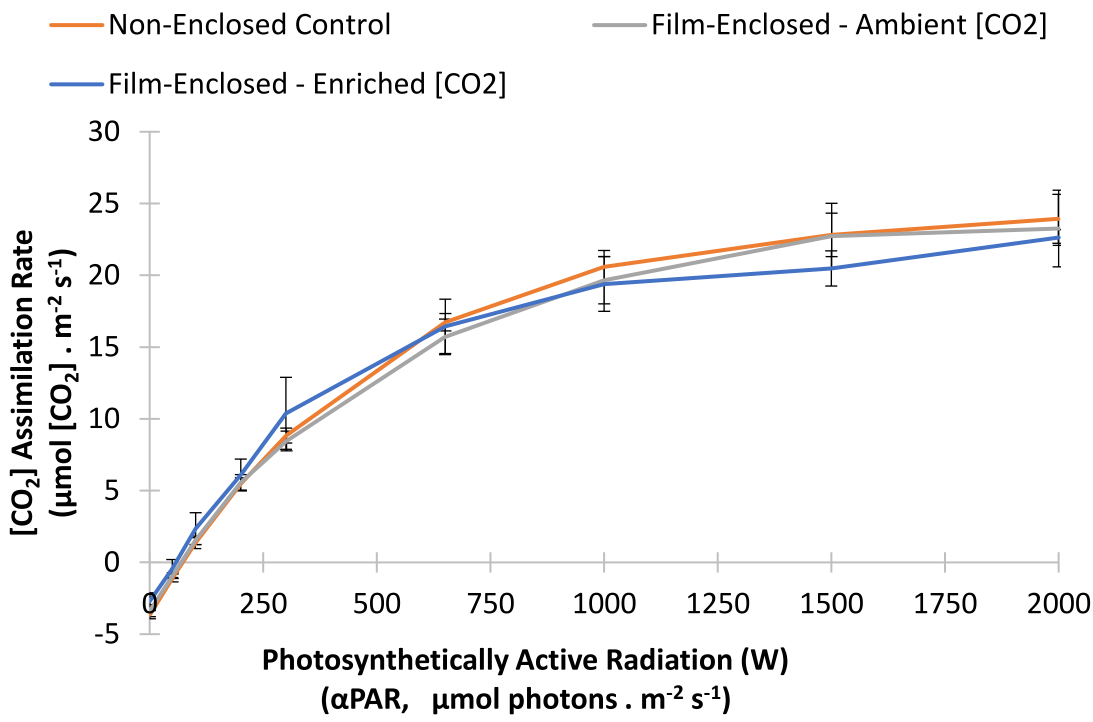


Figure 5.6 Mean leaf $[CO_2]$ assimilation at 25°C in response to PAR photon flux density. Observed differences between treatments were not significant at $\alpha = 0.05$. Bars represent the SEM

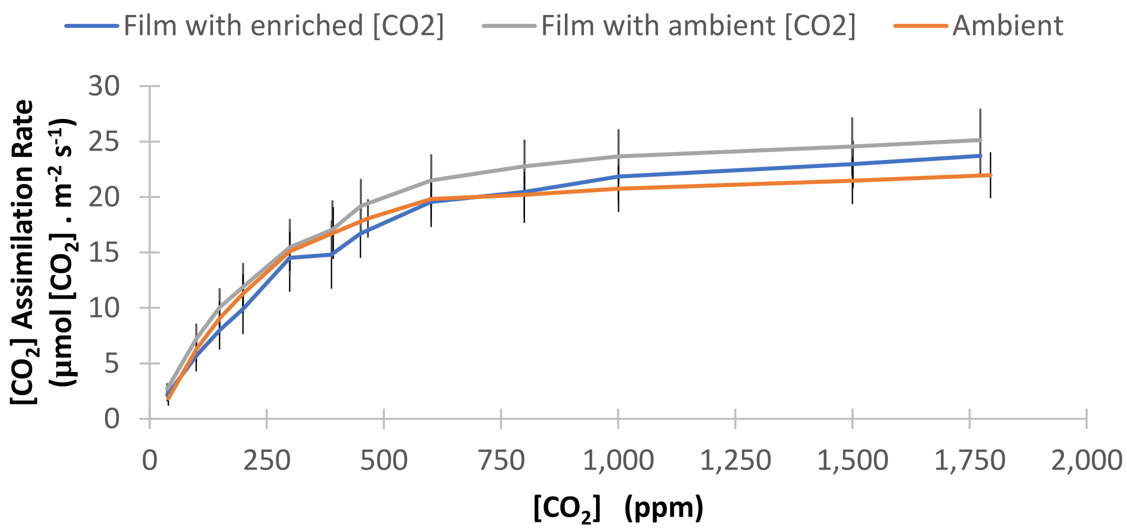


Figure 5.7 Mean leaf $[CO_2]$ assimilation rate at 25°C in response to atmospheric $[CO_2]$. Photosynthetic assimilation rates were higher at higher $[CO_2]$.

Table 5.2 [CO_2] assimilation parameters of early-sown maize seedlings at different C_a density when grown under an enriched [CO_2] film-enclosed environment, an ambient [CO_2] film-enclosed environment, and a non-enclosed environment. Numerical values represent treatment mean value and standard deviations. Significance codes were '***' 0.001; '**' 0.01; '*' 0.05; '.' 0.1.

Treatment	Vc_{max} (μmol m^{-2} s^{-1})	J_{max} (μmol m^{-2} s^{-1})	R_d (μmol m^{-2} s^{-1})	Γ* (μmol m^{-2} s^{-1})	K_m (μmol m^{-2} s^{-1})
Film with enriched [CO_2]					
Pre-removal	121.20 ± 23.24	80.55 ± 54.48	-3.76 ± 3.04	30.72 ± 0.99	413.30 ± 20.92
Post-removal	375.03 ± 27.62	54.48 ± 22.68	-9.89 ± 5.26	33.47 ± 3.22	475.57 ± 77.42
Film with ambient [CO_2]					
Pre-removal	168.07 ± 47.91	119.25 ± 33.15	-6.85 ± 1.29	32.84 ± 0.12	458.91 ± 2.67
Post-removal	104.76 ± 1.34	149.84 ± 5.95	-6.13 ± 1.05	32.24 ± 1.93	447.68 ± 42.91
Non-enclosed control					
Pre-removal	593.6 ± 425.39	91.84 ± 4.34	-5.60 ± 2.43	33.10 ± 0.05	465.02 ± 1.22
Post-removal	133.02 ± 39.99	108.00 ± 28.43	-5.49 ± 2.17	32.00 ± 1.08	441.26 ± 23.27
Significance (p value)					
Film	0.407	0.337	0.636	0.443	0.481
Pre/Post	0.278	0.632	0.288	0.852	0.777
Pre/Post*Film	0.036 *	0.625	0.080 .	0.031 *	0.029 *

5.4.5 Leaf Fluorescence and Chlorophyll Content

Leaf baseline fluorescence (F_0) was lower in film-enclosed treatments and higher in the non-enclosed ambient treatments whilst the film treatment was applied (Figure 5.8). Seedling leaf maximal fluorescence (F_m) was higher in both film-enclosed treatments with respect to the non-enclosed control treatment on most observation dates prior to film removal. The proportion of photo-excited electrons quenched by photochemical quenching (F_v/F_m) was also greater in film-enclosed treatments until film removal. Following film removal, treatment differences in baseline fluorescence, maximal fluorescence and photochemical quenching proportions (F_v/F_m) became non-significant as plants in the film treatment groups acclimated to ambient temperature conditions.

Leaf RCC also varied significantly throughout the observation period in response to daily ambient and headspace air temperature maxima (Figure 5.9). Leaf RCC was greater on most days in film-enclosed treatments when contrasted with the non-enclosed treatment, and responded to air temperatures. Following film removal (92 DAS), RCC decreased over six days in response to cooler maximum daily air temperatures, remaining only slightly greater than plants in the control treatment, indicating a temperature carryover effect. In the non-enclosed control treatment, leaf RCC was also greatest when maximum headspace temperatures remained within the biologically optimal temperature range, but decreased on cooler days when maximum headspace temperatures failed to enter the thermally optimal range. In the film-covered physiological observation period, these sub-optimal air temperature conditions occurred between 83-91 DAS. Differences in leaf chlorophyll content between naturally elevated and ambient [CO_2] conditions beneath clear polymer film were not significant.

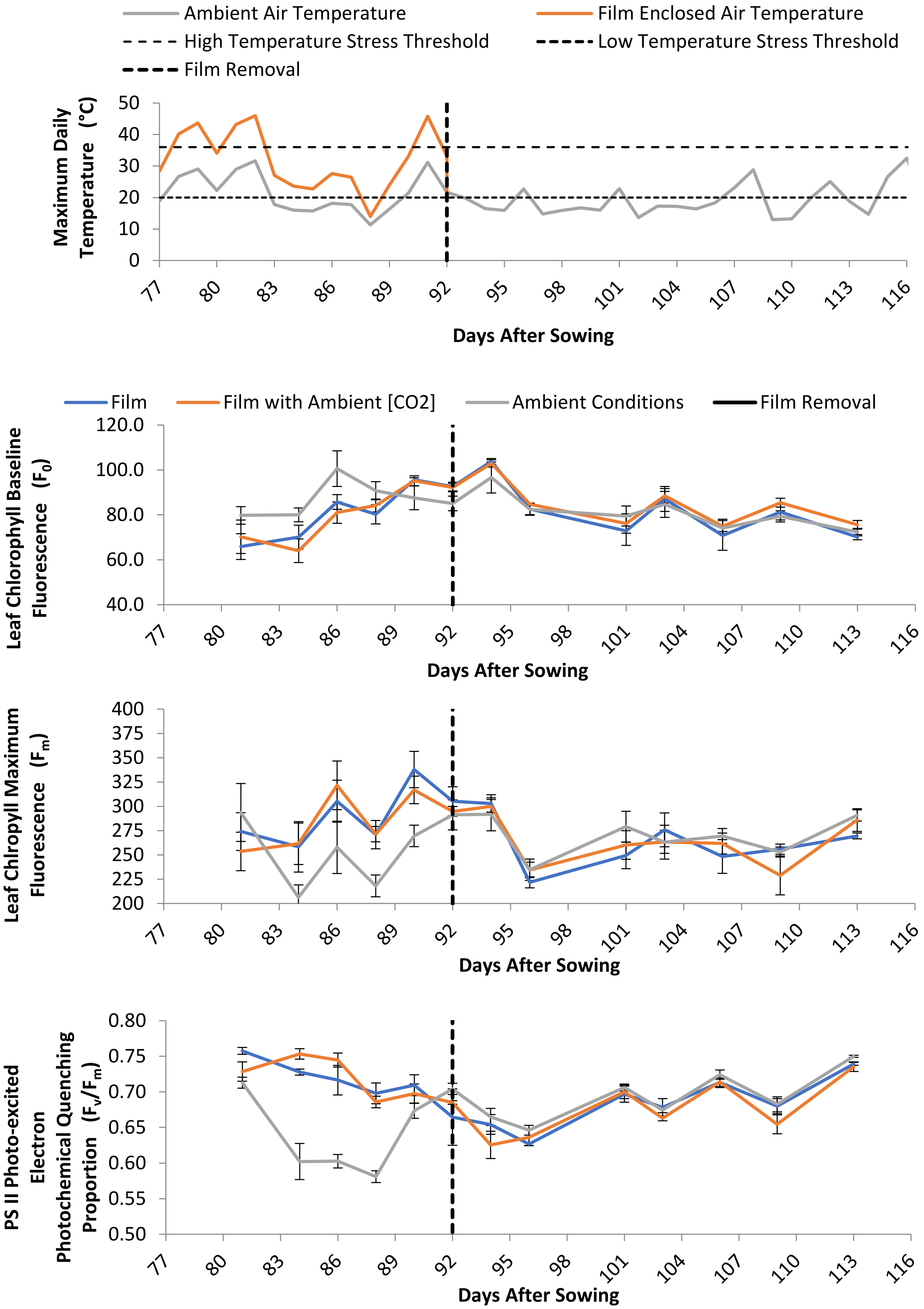


Figure 5.8 Air temperature, leaf baseline fluorescence (F_0), maximum fluorescence (F_m) and proportion of photo-excited electrons (F_v/F_m) in PS II undergoing photochemical quenching. Relative chlorophyll content of maize seedling leaves. All parameters converged rapidly following film removal. Values represent mean values ± SEM.

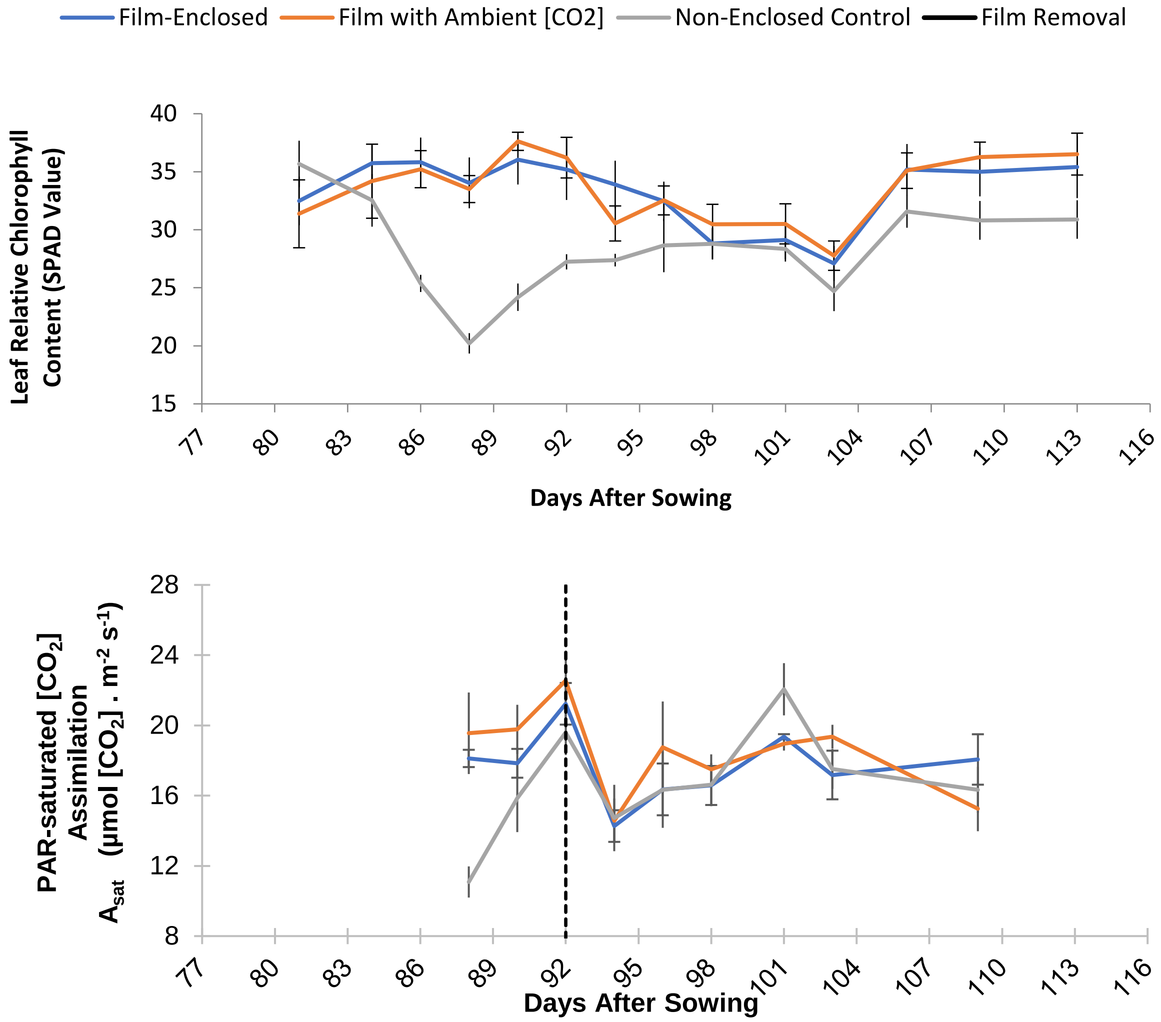


Figure 5.9 Relative chlorophyll content and PAR-saturated CO_2 assimilation rate (A_{sat}) of maize seedling leaves before and after film removal. Values represent mean values ± SEM.

5.5 Discussion

5.5.1 Temperature Effects

Previous studies have identified that the optimal headspace temperature for tropical maize production is 36 °C; beyond this, adverse effects of heat stress can decrease productivity and yield (Jones and Kiniry 1986; Carberry *et al.*, 1989; Muchow and Carberry, 1990). Throughout this experiment, maximum daily headspace temperatures were frequently within a range considered physiologically optimal for maize growth and development - 23-32 °C (Mahan *et al*. 1990) and the exponential growth response range of 14-23 °C (Walker 1969). These elevated temperatures enabled a more efficient accumulation of thermal time and extended window for efficient conversion of incident solar radiation into biomass production and plant development during this seasonal period (Mahan *et al*. 1990).

Without the protection of this insulating layer of film mean ambient air temperatures frequently did not exceed the minimum cardinal temperatures needed to support maize leaf elongation (7.3 ± 3.0 °C), stem growth (10.9 ± 1.4 °C) and root growth (12.6 ± 1.5 °C) (Sánchez *et al.*, 2014). Due to the close proximity of these minimum cardinal values to maximum ambient temperatures experienced throughout this season, we can conclude that even small increases in daily temperature maxima are likely to result in a significant increase in the duration and efficiency of plant biomass production (Walker, 1969).

5.5.2 Seedling Emergence Rate and Development

Low temperatures (5-15°C) have previously been demonstrated to retard maize germination, emergence and vegetative growth (Cal & Obendorf, 1972; Miedema, 1982). Establishment rates were low in the non-enclosed control, with 58% of sown seed completing emergence within 70 days of sowing. Emergence rates of early-sown seed were also low in the non-enclosed control treatment, with only 10% of planted seedlings emerging within 52 days of sowing. By contrast, film use during early sowing was associated with increased seedling establishment, as well as earlier and more uniform seedling emergence. Seedlings emerging in these treatments were also exposed every evening to cold temperatures similar in the non-enclosed control treatment, indicating that low establishment figures were not caused by acute cold stress overnight. Throughout the 93 days that seedlings were grown under film, film use increased thermal time accumulation by approximately 30%, resulting in the equivalent of 17 days development.

Comparison between high- and ambient-[CO_2] film-enclosed treatments showed that film-induced enrichment of [CO_2] within the headspace environment has little influence on seedling germination, emergence and vegetative growth, suggesting that temperature and moisture conservation are the main drivers of improved seedling establishment. These observations suggest that prolonged and/or persistent exposure to cold stress is more inhibitory than repeated brief exposure, and that increased daily exposure to warmer temperatures may alleviate emergence retardation in maize (Crafts-Brandner and Salvucci, 2002; Subsawat *et al.,* 2004).

Following initial emergence, use of film was associated with increased rates of seedling development and biomass production due to the changes identified above. Maize leaves growing under warmer film-enclosed treatments demonstrated increased rates of leaf area production and biomass production (Walker 1969; Tollenaar *et al.*, 1979; Itabari *et al.*, 1993). By contrast, seedlings exposed to colder ambient temperatures demonstrated slower leaf development and reduced leaf area during early growth (Muchow and Davis, 1988; Muchow *et al.*, 1990). These findings echo observations by other authors documenting temperature-linked changes in cell division, leaf initiation, and cellular expansion in maize (Walker 1969; Warrington and Kanemasu 1983; Miedema 1982; Miedema *et al.*, 1987; Imholte and Carter 1987; Rymen *et al.*, 2007).

In this trial it was observed that rates of biomass and leaf area production were not significantly different between seedlings growing in ambient- and enriched-[CO_2] conditions. In section 2.4.3 of this thesis it was also observed that film use can greatly enrich [CO_2], decreasing [O_2] within the enclosed headspace environment, and cause hypoxic conditions within the film environment; however, the absence of any discernible physiological or agronomic differences between film-enclosed plants grown under both enriched- and atmospheric-[CO_2] conditions is suggestive that headspace [O_2] was not a limiting metabolic substrate within film-enclosed conditions (Jackson, 1985). Such results provide evidence that prolonged exposure to headspace [CO_2] above ambient atmospheric concentrations has minimal long-term effects on the development and growth of maize seedlings in a film-enclosed environment, and that temperature is likely the sole driving force behind any improvements in crop health and performance.

5.5.3 Gas Exchange

Carbon assimilation rates are also strongly associated with stomatal conductance and CO_2 uptake and utilisation (Wong *et al.*, 1979). Following emergence, film enclosure was observed to significantly influence seedling stomatal activity, with modelling of individual seedling A/Ci and light-response curves indicating that seedlings exhibited no difference in light compensation point (g_0) or [CO_2] compensation point (Γ^*) when grown beneath film. Removal of film had no effect on seedling Γ^*, but did cause g_1 to increase and converge with g_1 of seedlings growing under ambient seasonal conditions. These changes in linear slope coefficient of stomatal activity (g_1) indicate that seedlings growing under film exhibit a lower water cost of carbon (λ) during [CO_2] assimilation (Medlyn *et al.*, 2011), but these benefits were not maintained following film removal.

Contrary to observations by other authors (Wang *et al.*, 2007; Hamilton *et al.*, 2008; Lopes *et al.*, 2011), differences in headspace [CO_2] had no discernible effect on seedling leaf fluorescence and chlorophyll concentration. Throughout this experiment, seedling RCC and chlorophyll fluorescence parameters were not significantly different between ambient and enriched-[CO_2] treatment groups during and after film enclosure. These similarities indicate that differences in headspace [CO_2] have minimal influence on [CO_2] assimilation and transparative heat loss in film-enclosed environments due to suppression of stomatal activity by high headspace VPD (Sinclair *et al.*, 2005; Fletcher *et al.*, 2007; Kholova *et al.*, 2010). These findings suggest that entrapment-driven [CO_2] accumulation has minimal effect on maize seedling growth and leaf development under conditions where [O_2] remains physiologically non-limiting (Jackson 1985), and that temperature and moisture conservation are the primary drivers of improved seedling development in maize.

5.5.4 Chlorophyll Fluorescence and Radiation Utilisation

Warmer conditions associated with film use were associated with reduced baseline chlorophyll fluorescence (F_0) and increased seedling ability to absorb and utilise photosynthetically active radiation (Genty *et al.*, 1996; Schreiber 2004). Under cold conditions, decreases in membrane fluidity and maximum enzyme reaction velocities slow biochemical reaction rates, impeding utilisation and movement of photo-excited electrons through photosystems I and II (Hochachka and Somero, 1984; Kingston-Smith and Foyer, 2000). Prolonged cold stress has also been shown to promote structural and functional changes to thylakoid membrane organisation, including migration and separation of the PS II light harvesting centre II (LHCII) from the core centre (Gounaris *et al.*, 1984), and de-stacking of the grana (Gounaris *et al.*, 1984; Sowinski *et al.*, 2005). Such changes limit the physical transfer of photo-excited electrons between PS II and PS I (Gounaris *et al.*, 1984; Sowinski *et al.*, 2005), promote prolonged photo-excitation of LHCII and increase baseline chlorophyll fluorescence (Mamedov *et al.*, 1993).

Use of film to increase seedling exposure to warmer temperatures improved seedling capacity for solar radiation absorption and utilisation under ambient early-season conditions. Maximal (F_m) and variable (F_v) leaf chlorophyll fluorescence were greater in both film-enclosed treatments, indicating increased density of photosynthetic pigments and light harvesting core (LHC) receptors in developed leaf tissues (Genty *et al.*, 1996; Schreiber 2004; Klughammer and Schreiber, 2008). Such changes increased the proportion of photoexcited electrons being transported for photosynthetic use (F_v/F_m), improving photosynthetic quantum efficiency (Schapendonk *et al.*, 1988; Lootens *et al.*, 2004). Film use also increased the relative chlorophyll content (RCC) of seedlings, with RCC higher due to reduced cold-induced photoinhibition and chlorophyll photooxidation (Fracehboud *et al.*, 1999; Lootens *et al.*, 2004; Janda *et al.*, 1996). Maximal fluorescence and RCC were greatest when temperature maxima were within the 23-32°C optimal temperature range (Mahan *et al.*, 2000) and decreased due to oxidative damage when daily maxima where outside these thresholds (Schapendonk *et al.*, 1988; Fracheboud *et al.*, 1999; Chen *et al.*, 2012). RCC loss associated with both heat- and cold-stresses are associated with photoinhibition (Savitch *et al.*, 2009) imbalances between photosynthesis and respiration (Fitter and Hay, 1987), changes in membrane fluidity and stability (Hochachka and Somero, 1984), the localised formation of reactive oxygen species (ROS) within the chloroplast (Leipner *et al.*, 2000; Aroca *et al.*, 2001; Aroca *et al.*, 2003), as well as reductions in antioxidant enzyme activity (Feierabend *et al.*, 1992; Gong *et al.*, 1997). Differences between these treatments quickly became insignificant following film removal, as plants became exposed to similar daily conditions and ambient temperature conditions, with maximal, baseline and variable fluorescence converging within seven days of removal. These effects indicate that film use improves PAR utilisation during film use but has no ongoing beneficial effects after film removal.

5.6 Conclusion

Film use had significant beneficial effects on both seed emergence percentages and the time required for emergence. Following emergence, increased temperatures under the film improved plant growth and development compared with the uncovered control. Passive [CO_2] accumulation and enrichment had minimal influence on leaf physiology and seedling development, and had no discernible effects on photosynthetic gas assimilation, PAR capture and utilisation. These findings suggest that film use can improve seedling establishment, agronomic development and photosynthetic physiology of maize growing under cold seasonal conditions. Following film removal most short-term physiological effects associated with film enclosure did not persist for more than four-six days. In the next chapter, APSIM will be used to estimate the productivity of forage and cereal maize production without film use at seven Tasmanian sites, so that yield benefits from film use can be identified.

Chapter 6: APSIM-based Biophysical Modelling of Existing Maize Production in Tasmania using APSIM

6.1 Abstract

Film has been used for several decades to support the production of maize and other tropical crops in cold-temperate regions of Europe, Canada, and the US. Maize is the only tropical cereal currently grown in Tasmania. In this chapter, a series of APSIM model scenarios was configured and run for a period of 65 years for seven sites across Tasmania. Minimum daily temperature was used to identify periods of frost risk due to the unavailability of historical frost observations in the climate record. Identical soil properties based on a bespoke Ferrosol from Elliott were used at each site, with agronomic practices based on the field-validated simulations of Pembleton and Rawnsley (2012).

Minimum seasonal temperatures, frost frequency and severity were affected by elevation and region (inland/coastal). Cold stress and frost risk varied considerably across all regions. Maximum daily growing season temperatures were warmer in inland regions compared with coastal regions between November and March but were colder than coastal sites from April onwards. Crop exposure to frost occurred most commonly between May and October across all sites. Site climate strongly influenced rates of plant development, with development occurring faster under the higher seasonal average temperatures. Regional differences in climate and frost exposure severity influenced maize forage and grain productivity.

6.2 Introduction

Film has been used for several decades to support the production of maize and other tropical crops in cold-temperate regions of Europe, Canada, and the USA (Kwabiah 2005; Lamont 2000; Crowley 1998). When used for maize production in these countries, film use has increased the quality and yield of maize grown for forage, cereal and sweet corn, and reduced the risks associated with frosts during spring and early autumn (Crowley 1998; Easson and Fearnehough 2000; Keane 2002; Bu *et al.*, 2013; Kwabiah 2004). Despite these benefits, film use is a relatively unknown technology in Tasmania and is not currently used to support maize production.

Maize is the only tropical cereal currently grown in Tasmania. Frost and cold stress are major constraints on maize productivity in all regions of Tasmania, occurring most frequently in inland regions, and maize is only planted near Tasmania's northern coast where these risks of frost and cold stress are smallest (Rawnsley *et al.*, 2007; Pembleton & Rawnsley 2012). The productivity and reliability of planting date recommendations and practices for maize production in coastal regions of Tasmania have been previously discussed by Pembleton and Rawnsley (2012), but to date no author has assessed the suitability of these practices in inland regions of Tasmania.

Traditionally, exploration of the regional performance of new crop production technologies like film would require grower production data and multi-location experiments to assess performance and understand relationships between sites and seasons and to characterise production environments. A more efficient means of estimating crop productivity is through the use of biophysical crop simulation models like APSIM (Keating *et al.*, 2003). These models simulate crop growth, development and productivity in response to climate, soil and management conditions (Hammer *et al.*, 2002; Keating *et al.*, 2003; Van Ittersum *et al.*, 2008; Adam *et al.*, 2010; Adam *et al.*, 2011). APSIM is widely used to simulate maize ontogeny and productivity in Australia (Birch *et al.*, 2008a; Birch *et al.*, 2008b; Carberry *et al.*, 2009; Pembleton and Rawnsley 2012; Chauhan *et al.*, 2013; etc.) and has been used to evaluate the effect of planting dates on forage maize productivity in coastal regions of northern Tasmania (Pembleton and Rawnsley, 2012). In previous chapters, biophysical models have been developed to quantify the benefits and risks of using film on the crop-growing environment. In this chapter, APSIM is used in conjunction with historical climate records to establish cold and frost incidence and the related impacts on crop failure rate, crop development, and crop productivity for forage and cereal crops grown in seven sites throughout inland and coastal Tasmania. The potential application of film technology to alleviate these temperature constraints is discussed, and the current cold and frost constraints on maize production in Tasmania are presented. This is explored in more detail in Chapter 7.

6.3 Materials and Methods

6.3.1 Simulation Configuration

A series of APSIM model scenarios was configured and run for a period of 65 years (1950/51 to 2014/15) using patched point climate datasets obtained from the SILO database (www.longpaddock.qld.gov.au/silo; Jeffrey *et al.* 2001) for seven sites across Tasmania (Table 6.1). Sites were selected to cover a range of differences in elevation and proximity to the coast, and differences across existing dairy and livestock production regions.

Table 6.1 Location details for seven agricultural sites in Tasmania

Site		Bothwell	Campbell Town	Cressy	Burnie	Devonport	Elliott	Forthside
Regional category		Inland / high	Inland / low	Inland / low	Coastal / low	Coastal / low	Coastal / high	Coastal / high
Latitude	(°S)	42.4	41.9	41.7	41.1	41.2	41.1	41.2
Longitude	(°E)	147.0	147.5	147.1	145.9	146.4	145.8	146.3
Elevation	(m)	352	209	136	8	10	155	127

Minimum daily temperature was used to identify periods of frost risk due to the unavailability of historical frost observations in the climate record, as per the methodology of Robertson *et al.* (1999). In these simulations, screen temperature thresholds less than 2 °C at 1.2 m elevation were identified as events conducive to frost occurrence (BoM 2016). Screen temperatures between 0 °C and 2.0 °C at 1.2 m were identified as light frost events, while temperatures <0 °C were identified as severe frost events. In the APSIM model, exposure to minimum temperatures between -2 °C and +2 °C at 1.2 m elevation initiates crop frost damage such as leaf senescence. Frost-induced crop failure was defined in the APSIM model as constituting sufficient leaf abscission to prevent post-frost crop growth and development.

Identical soil properties based on a bespoke Ferrosol from Elliott were used at each site to remove the confounding effect of soil variability (Table 6.2). Soil water content and mineral nitrogen concentration were reset prior to sowing in each simulated year. Key soil chemical, physical and nutrient properties are detailed in Table 6.2. The soil had no covering of surface organic matter prior to cultivation.

Table 6.2 Key physical, nutrient and soil water properties of the soil used for all sites

General Properties & Nitrogen Content								
Depth	Bulk Density	LL15	DUL	Maize PAWC	ρH	[OC]	$[NO_3^-]$	$[NH_4^+]$
	(g cm^{-3})	(mm/mm)	(mm/mm)	(mm)	(1 : 5 water)	(%)	(ppm)	(ppm)
0-20	0.8	0.21	0.34	26.0	6.9	0.7	1.0	10.0
20-36	0.8	0.21	0.33	19.2	6.5	0.7	2.0	6.0
36-48	1.0	0.3	0.42	14.4	5.5	0.4	1.0	0.3
48-80	1.0	0.31	0.43	38.4	5.5	0.3	1.0	0.1
80-110	1.1	0.36	0.49	39.0	5.5	0.2	0.0	0.0

Agronomic practices were based on the field-validated simulations of Pembleton and Rawnsley (2012). Forage maize was sown at 20 plants m^{-2} and harvested at the 50% milk stage (APSIM crop stage 8.5) to maximise potential biomass quality and yield. Cereal maize was sown at a density of seven plants m^{-2} and harvested at grain maturity (APSIM stage 12). Seed of cultivar A_110 was sown on 1 November at 30 mm depth with a basal fertiliser application of 100 kg/ha of urea. A second application of urea fertiliser was applied 45 days after sowing at a rate of 150 kg/ha to ensure nitrogen did not limit subsequent plant growth. Crops were irrigated to field capacity between sowing and harvest, with water applied whenever plants reached a 20 mm soil deficit.

6.3.2 Statistical Analysis

Each simulation generated development and productivity parameters including plant development status, stover content, grain protein content and yield, flowering and harvest dates, irrigation water consumption, and the number of light and severe frost events. Statistical analysis of these outputs was performed using SPSS v24 (IBM Australia, St Leonards, NSW Australia). Multivariate analysis of variance (MANOVA) was used to assess the significance of region on these parameters. Differences in climate- and site-based agronomic responses across multiple variables were determined using Wilke's Lambda (λ), with individual response variables assessed using analysis of variance (ANOVA), and different sites and climates identified using Tukey's Honest Significant Difference (HSD) method. Changes in the probability of crop failure for each site were assessed using logistic regression, with climate and site included as treatment variables.

6.4 Results

6.4.1 Climatic Conditions

Climatic conditions varied in response to both region and elevation without significant interaction. Maximum daily growing season temperatures were 1.0 - 2.2 °C warmer in inland regions compared with coastal regions between November and March but were colder than coastal sites from April onwards (Figure 6.1). Inland sites consistently experienced colder monthly minimum daily temperatures compared to coastal sites, with differences in minimum temperatures smallest during December and largest during June (Figure 6.1). As expected, elevation in each region type had a profound effect on the temperature profile. Across the inland sites, maximum and minimum temperatures were higher at the low-elevation sites of Cressy and Campbell Town when compared with the higher-elevation site at Bothwell (Figure 6.1). Similar trends were observed across the coastal sites, with low-elevation sites in Burnie and Devonport having higher minimum and maximum temperatures when compared with higher-elevation sites at Elliott and Forthside (Figure 6.1).

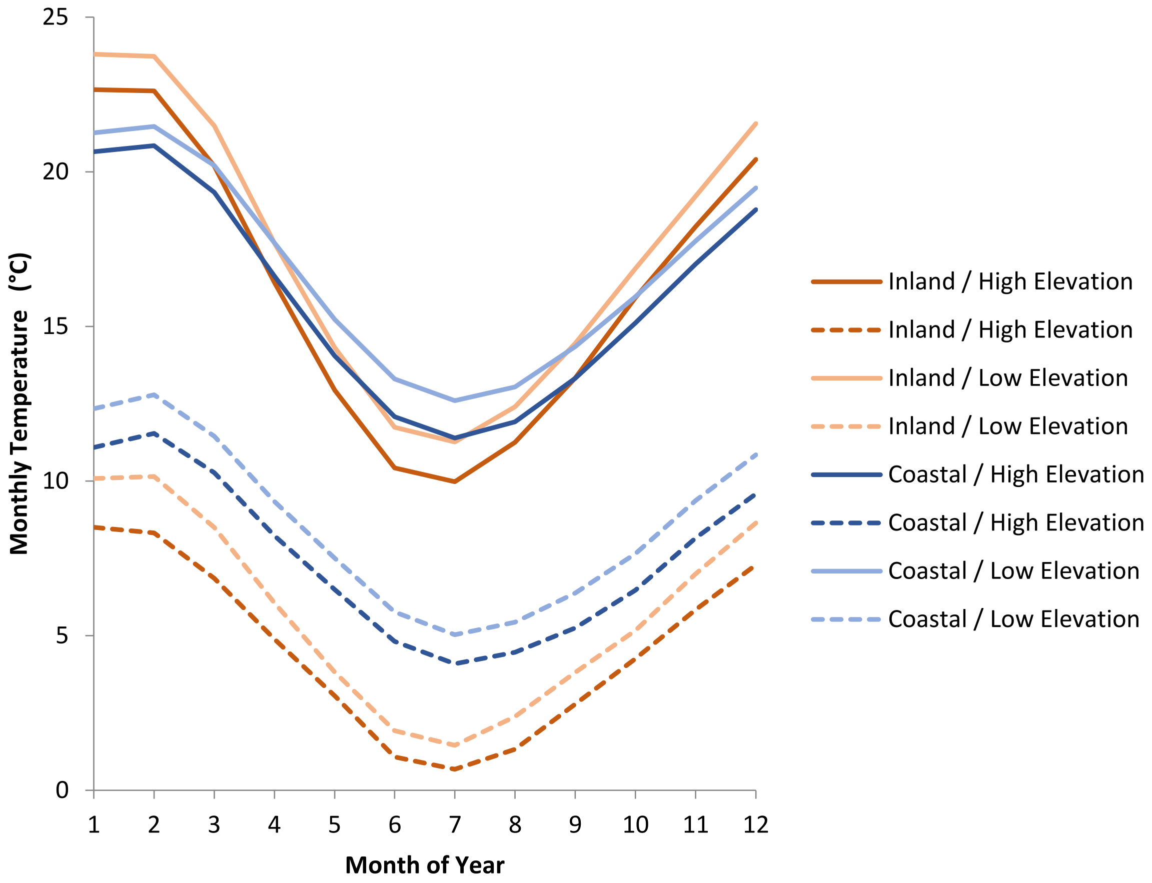


Figure 6.1 Long-term average monthly temperatures for inland and coastal sites at different elevations outlined in Table 4.1. Values represent the mean of daily maximum (solid line) and minimum (dotted line) temperature observations each calendar month.

6.4.2 Frost Conditions

Crop exposure to frost during the growing season varied significantly throughout the year, occurring most commonly between May and October across all sites (Figure 6.2). Light and severe frost events occurred more frequently at inland sites than coastal sites. Elevation had variable effects on frost incidence and severity, with severe frosts more common at the higher elevation sites.

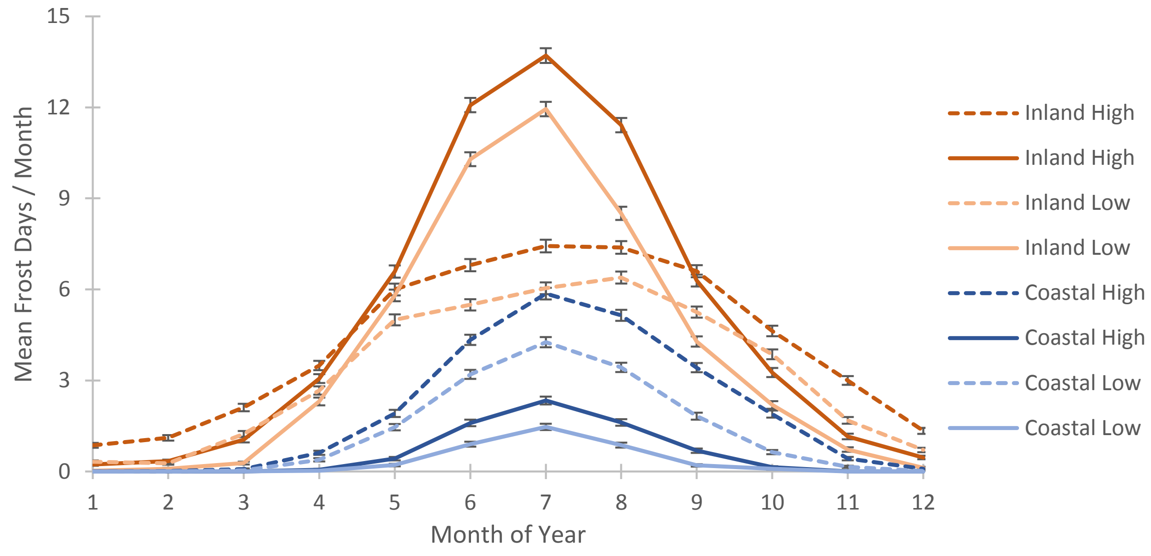


Figure 6.2 Mean number of potential frost days in each calendar month susceptible to light (0-2 °C, dotted line) and severe (< 0 °C, solid line) frosts. Error bars represent standard error of the mean (SEM) for each month.

6.4.3 Crop Development

Site climate strongly influenced rates of plant development ($p < 0.001$), with development occurring faster under the higher seasonal average temperatures prevailing at the coastal / lower elevation sites compared with inland / higher elevation sites (Table 6.4). Flowering occurred three days earlier at the lower-elevation, inland sites of Cressy and Campbell Town compared with the lower-elevation / coastal sites of Burnie and Devonport, respectively (Table 6.4). Flowering was delayed to around 12 February at the elevated / inland Bothwell site, and February 10-14 for the elevated / coastal sites of Forthside and Elliott.

Similar regional differences in crop development occurred during grain filling (Table 6.4). Lower inland regions reached the forage harvesting stage (50% milk) the earliest, on 27 March, followed by lower coastal regions on 30 March. Cooler seasonal temperatures experienced in elevated, inland regions delayed forage harvesting until 13 April, and between 7 and 17 April in coastal regions. These site-based differences in crop development became even more pronounced when the crop was grown to maturity, with mean crop development times differing by as much as 39 days between Cressy (8 May) and Elliott (16 June).

6.4.4 Crop Productivity

Maize forage and cereal productivity varied in response to crop frost exposure severity ($p < 0.001$). Frost severity reduced maize productivity and crop biomass when grown for forage ($p < 0.001$) (Table 6.5). In crops grown for grain, frost severity decreased the yield and protein content of harvested grain (Table 6.6). This effect was consistent across all sites and did not interact with site climate ($p = 0.3$). Severe frost exposure was also associated with reduced grain number and cereal stover at some sites, but this trend was inconsistent across sites.

Regional differences in climate influenced crop forage and grain productivity ($p < 0.001$). Forage yields were highest in lower elevation / inland and lower elevation / coastal regions where there were relatively few frosts, with the highest yields in Devonport, Forthside and Burnie, respectively (Table 6.5). Grain protein was greatest for crops grown at Cressy and Campbell Town and smallest for Elliott and Forthside (Table 6.6). Grain yield did not vary significantly between regions, with mean grain weight and number greatest in Devonport, Burnie and Cressy, and lower in Campbell Town, Forthside, Elliott and Bothwell, respectively.

Table 6.3 Number of days from sowing to key development stages for simulated medium maturing (110 CRM) maize crops sown on 1 November at seven Tasmanian locations. Development periods were calculated individually for each year, with presented values representing the mean of all observations ± SEM.

	Bothwell	Campbell Town	Cressy	Burnie	Devonport	Elliott	Forthside
Cumulative development time							
Days to flowering	103 ± 1	96 ± 1	95 ± 1	98 ± 1	99 ± 1	106 ± 1	102 ± 1
Days to forage harvest	163 ± 2	147 ± 1	146 ± 1	149 ± 1	150 ± 1	167 ± 2	156 ± 1
Days to grain maturity	217 ± 2	195 ± 1	191 ± 1	198 ± 1	202 ± 1	230 ± 2	212 ± 1
Crop development dates							
Flowering	11-Feb	4-Feb	3-Feb	6-Feb	7-Feb	14-Feb	10-Feb
Forage Harvest	13-Apr	28-Mar	27-Mar	30-Mar	31-Mar	17-Apr	7-Apr
Grain Maturity	4-Jun	12-May	8-May	15-May	18-May	16-Jun	29-May

Table 6.4 Simulated forage biomass productivity of medium maturing (110 CRM) forage maize crops sown on 1 November at seven Tasmanian locations. Values represent the mean of all observations ± SEM. Where no standard error is provided, this effect was only observed once in 65 years of simulations, whilst N/A signifies that this effect was not observed in any simulation.

	Bothwell	Campbell Town	Cressy	Elliott	Forthside	Burnie	Devonport
Cumulative forage seasonal frost risks (%)							
No frost	3.1	24.6	35.4	67.7	81.5	95.4	92.3
Light frost only	23.1	47.7	38.5	26.2	15.4	4.6	6.2
Severe frost only	32.3	12.3	20.0	6.2	3.1	0.0	0.0
Frost-induced crop failure	41.5	15.4	6.2	0.0	0.0	0.0	1.5
Mean frost exposure events (season^{-1})							
Light frost	6.4 ± 0.8	1.8 ± 0.2	1.9 ± 0.2	0.4 ± 0.1	0.2 ± 0.0	0.0 ± 0.0	0.1 ± 0.0
Severe frost	4.0 ± 0.5	0.5 ± 0.1	0.6 ± 0.1	0.1 ± 0.0	0.03 ± 0.0	0.0 ± 0.0	0.05 ± 0.0
Forage biomass (tonnes DM ha^{-1})							
Frost-free	26.5 ± 0.5	27.5 ± 0.2	28.4 ± 0.1	27.4 ± 0.2	28.7 ± 0.1	29.1 ± 0.1	27.6 ± 0.2
Light frost	25.5 ± 0.4	27.3 ± 0.2	28.3 ± 0.5	25.9 ± 0.5	28.0 ± 0.3	29.0 ± 0.4	27.8 ± 0.2
Severe frost	21.9 ± 0.7	26.6 ± 0.9	N/A	24.5 ± 1.0	28.0 ± 0.2	N/A	26.6 ± 0.4
Fatal frosts	14.9 ± 1.8	13.6 ± 3.8	N/A	N/A	N/A	22.9	17.3 ± 6.7
Mean forage biomass	20.0 ± 0.9	25.1 ± 0.8	28.4 ± 0.1	26.8 ± 0.2	28.5 ± 0.1	29.0 ± 0.1	26.9 ± 0.5

Table 6.5 Simulated cereal productivity of medium maturing (110 CRM) cereal maize crops sown on 1 November at seven Tasmanian locations. Values represent the mean of all observations ± SEM. Where no standard error is provided, this effect was only observed once in 65 years of simulations, whilst N/A signifies that this effect was not observed in any simulation.

	Bothwell	Campbell Town	Cressy	Elliott	Forthside	Burnie	Devonport
Cumulative seasonal frost risks (%)							
No frost	3.1	15.6	23.4	67.2	81.3	95.3	92.2
Light frost only	3.1	10.9	14.0	24.9	12.4	4.7	6.2
Severe frost only	0.0	3.1	3.1	1.6	1.6	0.0	0.0
Frost-induced crop failure	93.8	70.4	59.4	6.3	4.7	0.0	1.6
Grain frost exposure events (season^{-1})							
Light frost	6.4 ± 0.8	1.9 ± 0.2	6.4 ± 0.8	0.0 ± 0.0	0.1 ± 0.0	0.4 ± 0.1	0.2 ± 0.0
Severe frost	4.0 ± 0.5	0.6 ± 0.1	4.0 ± 0.5	0.0 ± 0.0	0.05 ± 0.0	0.1 ± 0.0	0.03 ± 0.0
Grainyield (dry weight t ha^{-1})							
Frost-free	9.2 ± 0.3	11.3 ± 0.3	12.0 ± 0.2	9.8 ± 0.2	11.2 ± 0.2	12.1 ± 0.1	11.8 ± 0.3
Light frost	7.3 ± 0.6	11.4 ± 0.5	9.3 ± 0.7	7.2 ± 0.3	9.1 ± 0.3	10.5 ± 0.6	11.0 ± 0.4
Severe frost	0	8.2 ± 1.1	0	4.2	7.8	N/A	8.2 ± 0.6
Grain number ('000's m^{-2})							
Frost-free	3.65 ± 0.03	3.81 ± 0.08	3.82 ± 0.05	3.54 ± 0.06	3.73 ±?	3.85 ± 0.05	3.83 ± 0.06
Light frost	3.36 ± 0.20	3.88 ± 0.11	3.39 ± 0.32	2.95 ± 0.17	3.53 ±?	3.83 ± 0.15	4.02 ± 0.07
Severe frost	0	3.06 ± 0.94	0	1.73	3.68	N/A	3.71 ± 0.55
Grain protein (%)							
Frost-free	8.56 ± 0.01	8.73 ± 0.08	8.36 ± 0.04	8.17 ± 0.06	8.14 ± 0.04	8.24 ± 0.03	8.83 ± 0.06
Light frost	8.27 ± 0.05	8.72 ± 0.16	7.89 ± 0.08	7.49 ± 0.12	7.83 ± 0.14	8.29 ± 0.27	8.61 ± 0.08
Severe frost	0	8.02 ± 0.06	0	6.57	7.61	N/A	8.17 ± 0.40

6.5 Discussion

Minimum seasonal temperatures, frost frequency and severity were affected by regional geography. Increases in elevation were associated with small (~2.0 °C) decreases in daily minimum temperatures in inland and coastal regions. Minimum daily temperatures were 1.0-2.5 °C colder at inland sites than at coastal sites of similar elevation. When combined, these effects caused minimum daily temperature conditions to be up to 4.5 °C colder in inland sites than in existing maize production regions in coastal areas, increasing the incidence and severity of frost events in inland regions.

Cold stress and frost risk varied considerably across all regions. Temperatures throughout the growing season were significantly lower than the physiologically optimal 23-32 °C temperature range for maize production, thus constraining and slowing crop development in all regions. Crops grown in warmer regions completed flowering and harvesting earlier than colder sites, indicating that they were less constrained by cold temperatures. Seasonal maximum temperatures decreased in response to increased elevation and were between 0-3 °C warmer between August and May in lowland and high coastal sites of similar elevation due to the maritime climate effect. Due to these combined effects, maximum seasonal temperatures in low inland and coastal regions were up to 2.5 °C than high inland and coastal regions. Regional temperature differences delayed forage maturity in the inland / elevated regions by as much as 22 days and slowed grain maturity by up to 39 days, extending the crop's exposure to frost. In addition, these delays coincided with increased frost severity and frequency in all regions, increasing the risk of frost damage and subsequent yield and quality reductions. This relationship was especially significant amongst inland sites, where autumnal frosts events were more severe and occurred earlier and more frequently than in coastal regions.

Frost was a substantial constraint on the productivity of maize crops grown for grain. Cereal crops experienced higher rates of frost-induced crop damage and failure than forage crops due to the later maturity and harvest of these crops. These differences in crop maturity dates ensured that cereal crops were more likely to experience fatal or severe frost damage, rather than light or no damage. Mean grain yields were similar to other irrigated maize production regions of Australia during seasons unaffected by frosts (GRDC 2009) but decreased significantly in response to earlier frost-onset frequency, and severity. Productivity losses caused by exposure to frost events were more pronounced in grain crops than in forage crops, with grain crops losing between 10-90% of simulated grain mass after exposure to severe frost events. Exposure to severe frosts also reduced cob quality across most sites due to reductions in grain density and protein content, reducing crop value.

Mean forage yields across Tasmanian sites used in these simulations were not significantly different if not exposed to frost, averaging between 27.3 ± 0.5 and 28.2 ± 0.5 t ha^{-1} DM in inland and coastal regions respectively. These frost-free forage yields were higher than mean forage yields in regions where autumn frost occurs early in the season and crops were more likely to be exposed to increasingly frequent and severe frost events. In these sites yields decreased significantly in seasons severely or fatally affected by frost, and may be less digestible, have poorer ensilation qualities and nutritional value for livestock (St Pierre *et al.* 1983; Narasimhalu *et al.* 1986).

Frost events occur frequently in inland Tasmania throughout the maize growing season and are likely to occur earlier and be more damaging in frost-prone areas. Frost-induced crop failure will occur frequently in these areas, with 6-41% of forage crops and 60-93% of cereal crops likely to fail. Surviving cereal crops are unlikely to be highly productive due to frequent frost damage and will exhibit signs of frost exposure and damage, reducing the suitability of forage biomass for ensilation (St Pierre *et al.* 1983; Narasimhalu *et al.* 1986). In these regions, technologies like film that increase growing environment temperatures and protect against frost may significantly improve crop security, productivity, and profitability (Crowley 1998; Lamont 2008; Kwabiah 2005; Marmont 2004).

In existing coastal regions frost rarely occurs during the maize growing season and can be effectively managed by planting early during November and using maize cultivars with an appropriate CRM (Pembelton and Rawnsley, 2012; Rawnsley 2007). For irrigated crops grown in this area, the risks of frost-induced crop damage were low and productivity is climatically constrained by cold seasonal conditions only. In these regions, protection of seedlings from frost is unlikely to significantly reduce rates of crop failure. Despite this, low-cost technologies like film use may still be beneficial for forage and cereal maize production in these areas, if film can successfully improve growing season temperatures and alleviate symptoms of cold stress (Kwabiah 2005; Lamont 2008). These findings indicate that maize (as a model tropical cereal species) is limited in cool and elevated areas of Tasmania and may benefit from film use.

6.6 Conclusion

The productivity of simulated forage maize crops in Tasmania was adversely influenced by regional differences in temperature and frost exposure. Forage and cereal maize yields in inland regions were highest in crops with light or no exposure to frost, indicating that film represents one low-cost approach for protecting crops from frost and cold stress during early growth. Crop exposure to frost at each site was related to seasonal minimum climate temperatures, which were exacerbated by localised differences in elevation. Frost exposure occurred infrequently in coastal production areas but was a major limitation to forage and cereal maize productivity in inland sites. These findings indicate that the viability and productivity of maize (as a model tropical cereal species) is limited in cool and elevated areas of Tasmania and may benefit from film use. In the next chapter, headspace climate and crop growth are modelled to identify the optimal sowing and film-enclosure times for maize in different regions and estimate differences in productivity between proposed and existing maize production systems in Tasmania.

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Chapter 7: Biophysical Modelling of Film Suitability in Maize Using APSIM

7.1 Abstract

Use of transparent film is proposed to mitigate the cold and frost risks associated with earlier planting dates of maize in Tasmania. Film use can protect enclosed seedlings from damage caused by frost and snow but has the potential to damage maize seedlings between late spring and early autumn due to excessive heat-trapping. Due to these conflicting temperature effects, it is uncertain what time of year film should be incorporated into Tasmanian maize production systems, and whether doing so will have positive or negative long-term effects on maize productivity, variability and yield. This chapter analyses the results of a systems modelling study into the effects of film use for maize production in different agricultural regions of Tasmania using APISM. Planting began on 15 July and occurred at 14-day intervals until 23 September. Four maize cultivars with different comparative relative maturity (CRM) rates were used. Soil and agronomic practices used in these simulations were otherwise identical to those described in Chapter 6, with adjustments made for changes in planting date.

The modelling presented shows that incorporating film use during seedling growth improved the resilience and reliability of early-sown forage maize production systems at frost-susceptible inland sites. Adoption of film-protected early planting dates with late-maturing cultivars enabled forage maize to be successfully planted, grown, and harvested earlier, effectively extending the potential maize growing season. Film use decreased crop failure risks in early-sown systems and increased rates of crop development across all sites, bringing forward flowering and harvest dates. The long-term productivity effects of film use differed between inland and coastal regions due to changes in headspace temperature. In this way, widespread adoption and use of film is likely to increase the long-term productivity of maize forage crops planted in Tasmania.

7.2 Introduction

Use of film is proposed to mitigate the cold and frost risks associated with earlier planting dates. Film use has been demonstrated to increase seedling emergence, leaf development, leaf area and growth rates due to the generation of warmer temperatures favourable for maize growth under cold seasonal conditions (see Chapter 5). Film use can have other secondary benefits, including improving soil moisture retention (Braunack *et al.*, 2015) and reducing water vapour and [CO_2] emissions (Lisson *et al.*, 2016) until the film degrades or is removed. However, the heat-trapping effects caused by film use can potentially damage maize seedlings on sunny days between late spring and early autumn, reducing crop productivity. Due to these conflicting temperature effects, it is uncertain whether film use will increase or decrease the productivity of tropical cereal species like maize in Tasmania.

To maximise the grower benefits from film use, it is important to identify optimal combinations of early planting dates, film enclosure duration and cultivar maturity rates. In Chapter 3 it was shown that film cannot be safely combined with November planting dates, since headspace and soil temperatures frequently exceed the fatal temperature threshold for maize and other tropical crops (Birch 2008; Katan *et al.*, 1990). Whilst long-term experiments across a range of regions could provide such information, the investment of time and financial resources associated with undertaking such studies would be prohibitive. A cost-effective alternative approach is to use APSIM simulations that estimate crop growth and development based on climate, soil, and management practices. This approach has previously been used to accurately explore the yield potential and WUE of maize and lucerne grown across a range of Tasmanian pastoral regions (Pembleton and Rawnsley 2012; Pembleton *et al.* 2011). Robertson *et al.* (1999) have similarly used biophysical modelling to explore the effect of maturity type and sowing date on the risks of frost exposure for other crops (e.g. canola) grown in the northern wheat belt of eastern Australia.

This chapter analyses the results of a systems modelling study into the effects of film use for maize production in different agricultural regions of Tasmania using APISM (Keating *et al.* 2003). The study explores the interactions between planting date, film use and cultivar genotype and the effect on silage maize yield security and productivity across four contrasting dairy regions in Tasmania.

7.3 Materials and Methods

7.3.1 Simulation Construction

APSIM (Keating *et al.*, 2003) was used to develop biophysical simulations of maize initially planted and grown beneath film. Planting began on 15 July and occurred at 14-day intervals until 23 September. Four maize cultivars (A100, A110, A120, A130) were planted representing differences in comparative relative maturity (CRM), but with otherwise identical physiological behaviour. After planting, crops were grown under film for durations of between 0 to 70 days, with film removed at 14-day intervals. Agronomic practices used in these simulations were otherwise identical to those described in Chapter 6, with adjustments made for changes in planting date. Crops were irrigated to field capacity between sowing and harvest, with water applied whenever plants reached a 20 mm soil deficit. Comparisons of crop productivity, frost exposure and failure rate were made to appropriate simulation outputs presented in Chapter 6.

Soil properties used in these simulations were identical to those used in Chapter 6 and were used at each site in order to isolate the climate response and remove the confounding effects of soil variability. These properties were derived from a bespoke Ferrosol from Elliott and are outlined in Table 6.2. Soil water content and mineral nitrogen concentration were reset just prior to sowing in each year. The soil had no covering of surface organic matter prior to cultivation.

Simulations were run for 65 years (1950/51 to 2014/15) using site-specific climate data for four locations in Tasmania; namely Bothwell (42.4°S, 147.0°E), Campbell Town (41.9°S, 147.5°E), Devonport (41.2°S, 146.4°E) and Elliott (41.1°S, 145.8°E), with patched point climate datasets for each site obtained from the SILO database (www.longpaddock.qld.gov.au/silo; Jeffrey *et al.*, 2001). Sites were selected based on diversity of climates and proximity to existing dairy regions. Collective 'all soils' models presented in Table 3.1 were used within the film-enclosed headspace. These models were used to estimate daily maximum temperature, minimum temperature and solar radiation exposure during periods when the headspace was enclosed by film and were incorporated into the APSIM modelling framework using the methodology described in 3.2.4.

APSIM's default temperature interpolation model was used to calculate daily temperature exposure and radiation use efficiency. This model is a non-accessible part of APSIM's core programming and cannot be edited or overwritten by APSIM users. This software architecture precluded the use of more accurate temperature interpolation model described in 3.3.4 during crop simulations.

During simulations, frost-induced crop failure was defined in the APSIM model as leaf damage and loss of leaf area sufficient to prevent subsequent crop growth and development. In the APSIM model, exposure to minimum temperatures between -2 °C and +2 °C at 1.2 m elevation initiates frost damage and leaf senescence, using the methodology described in 4.2.1. To prevent crops experiencing frost damage during periods of film enclosure, a rule was introduced preventing minimum temperatures from dropping below 2.0 °C. This minimum temperature prevents frost-induced leaf abscission but is below temperature thresholds needed for crop growth and development (Brown *et al.*, 2014).

7.3.2 Statistical Analysis

Each simulation reported development and productivity parameters including crop biomass, development, flowering and harvest dates, irrigation totals, and the number of light and severe frost events. Statistical analysis of these outputs was performed using SPSS v24 (IBM Australia, St Leonards, NSW Australia). At each location, multivariate analysis of variance (MANOVA) was used to assess the significance of planting date, cultivar maturity rate (CRM) and film duration on crop forage flowering dates, harvest dates and biomass using Wilke's Lambda (λ). Responses of individual output variables were assessed using analysis of variance (ANOVA), with differences between planting dates, cultivar CRM, and film duration identified using Tukey's Honest Significant Difference (HSD) method. Effect magnitude was estimated at each site using linear regression, with site planting date, cultivar CRM and film duration included as treatment variables. Crop exposures to light and severe frost events were included as covariates. Changes in the probability of crop failure for each site were also assessed using logistic regression, with site, planting date, cultivar and film duration included as treatment variables.

7.4 Results

7.4.1 Crop Development

Crop development rates varied significantly by site, with Campbell Town and Devonport reaching flowering and maturity earlier than Bothwell and Elliott. Film use increased rates of crop development, bringing forward flowering and harvest dates. Increases in crop development rate was influenced by the duration of film use, with extended film use causing greater advances in mean flowering and harvest dates (Figure 7.1; Figure 7.2). Increases in crop development rate caused by film use changed seasonally in response to planting date, with the large advances occurring in July and smaller advances occurring in August and September (Figure 7.1; Figure 7.2). Cultivar CRM also influenced development dates across all sites, with all cultivars reached maturity within 18-23 days of each other (Figure 7.1; Figure 7.2; Figure 7.3).

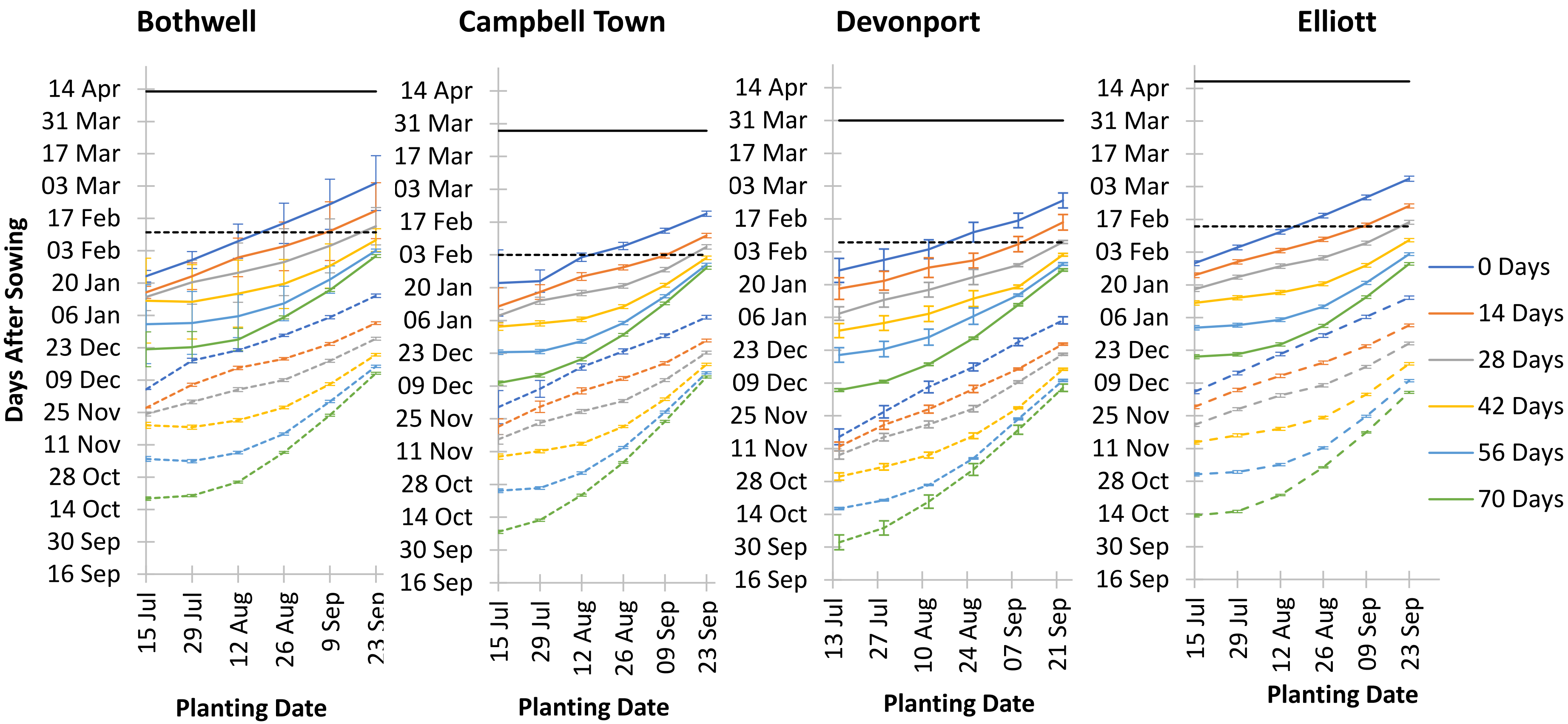

Figure 7.1 Effect of film duration on mean flowering and maturity dates of early-sown 100 CRM maize. Coloured lines depict the mean flowering (dotted line) and harvest (solid line) dates, whilst horizontal black lines depict mean flowering (dotted line) and harvest (solid line) dates using existing production practices. Bars represent the SEM.

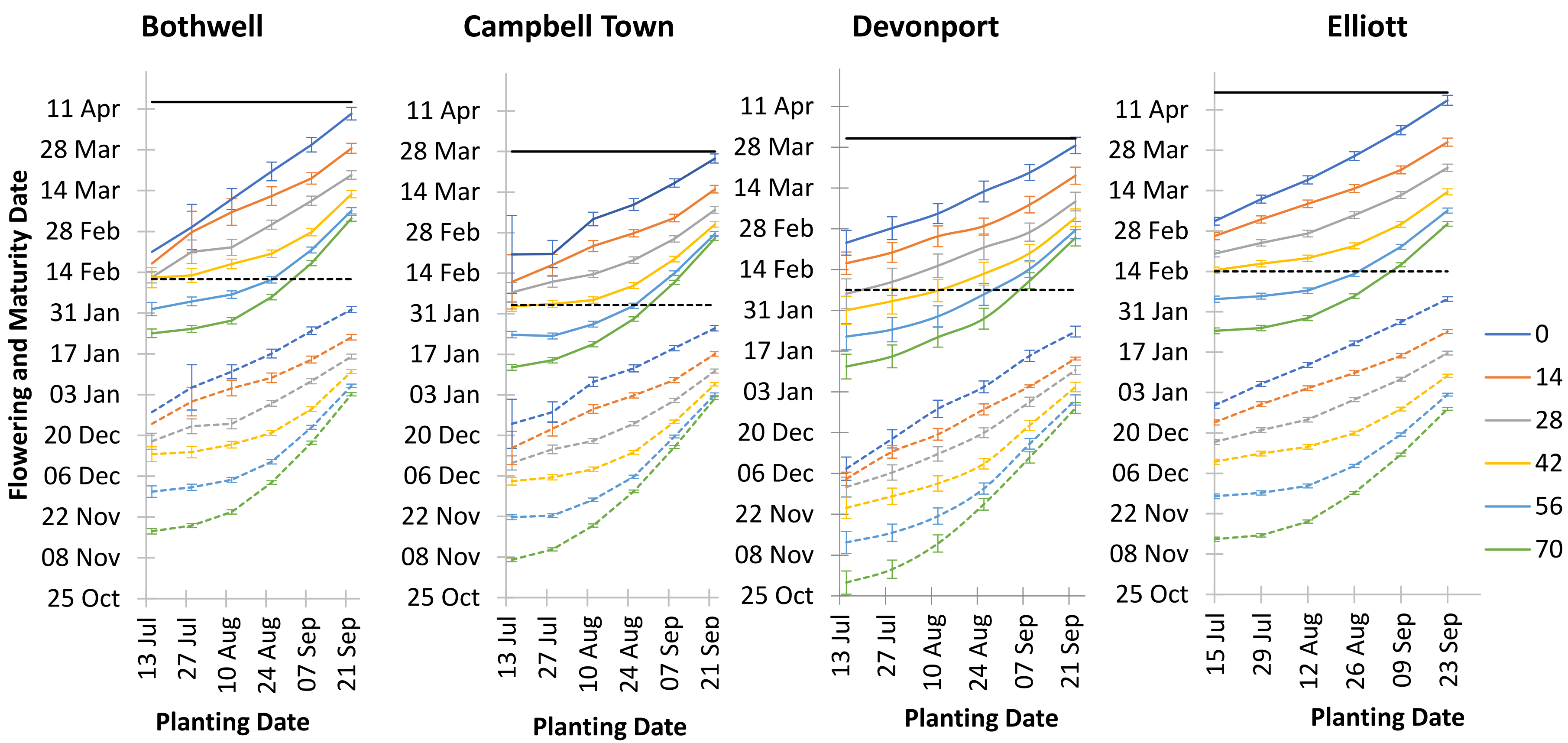

Figure 7.2 Effect of film duration on mean flowering and maturity dates of early-sown 130 CRM maize. Coloured lines depict the mean flowering (dotted line) and harvest (solid line) dates, whilst horizontal black lines depict mean flowering (dotted line) and harvest (solid line) dates using existing production practices. Bars represent the SEM.

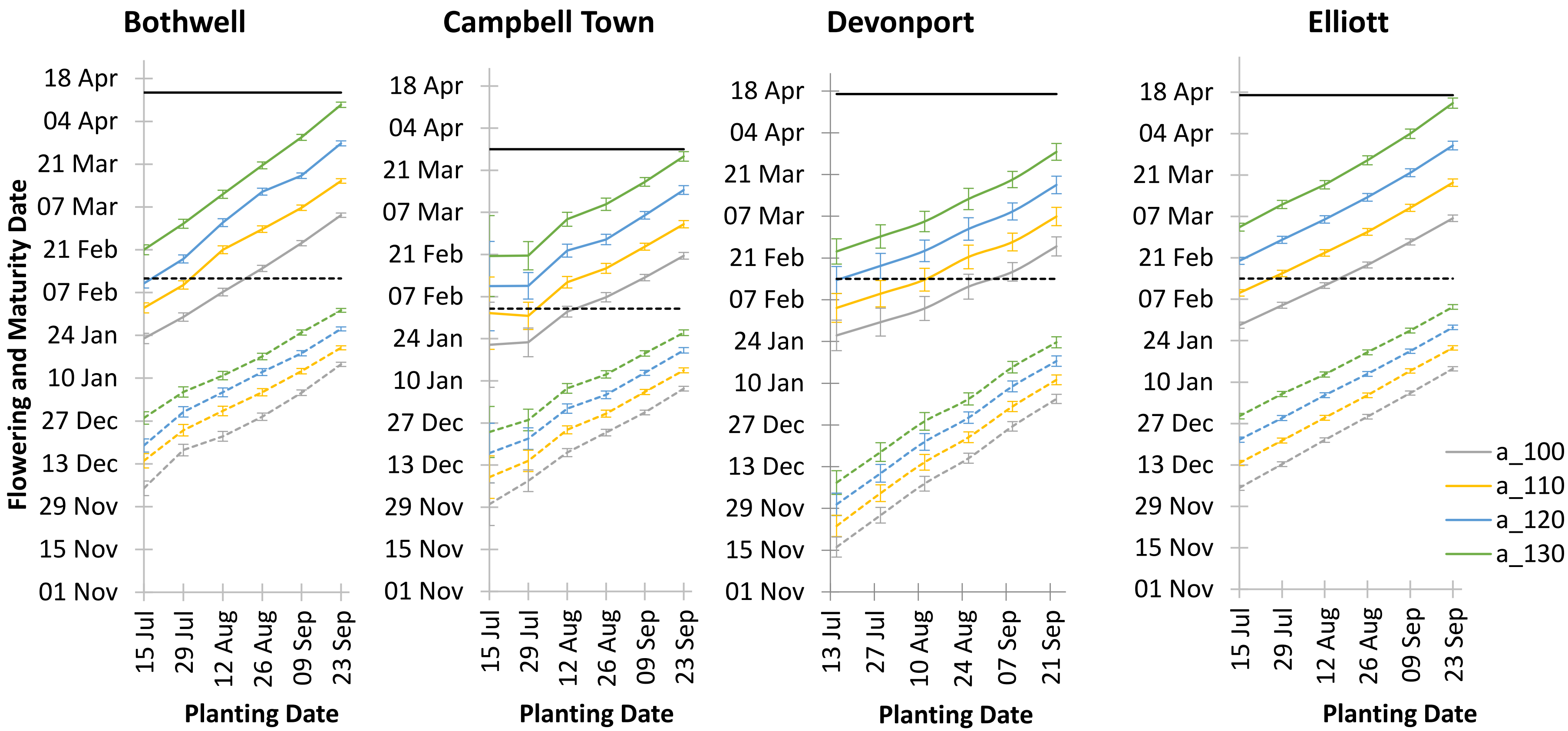

Figure 7.3 Mean date of flowering (dotted lines) and harvest (solid lines) of maize grown without film after being sown on different planting dates. Line colour denotes different cultivar comparative relative maturity (CRM), whilst horizontal black lines represent mean flowering (dotted line) and harvest (solid line) of existing cultivars (110 CRM) grown using existing production practices. Bars represent the SEM.

7.4.2 Film Effects On Crop Biomass Under Frost-free Conditions

Film had mixed effects on maximum biomass yields in inland sites. Film use increased the availability of forage biomass at harvest in the inland sites of Bothwell and Campbell Town for crops planted between 15 July and 10 August and grown under frost-free conditions (Figure 7.4). Use of film caused reductions in harvest yields at these sites when planted after this period due to increasingly acute heat stress.

Film use universally decreased maximum biomass yields in the coastal sites of Devonport and Elliott when grown under frost-free growing conditions (Figure 7.5). Yield reductions caused by film use were least severe (3-5 t ha^{-1}) in crops planted during July but increased in severity when crops were planted later throughout August and September.

Across all sites, film use caused only small changes in biomass yields when used for short durations ($p < 0.001$). Yield effects caused by film use were dependent on region and planting date ($p < 0.001$) due to changes in headspace temperature. Film-induced reductions in biomass yields were able to be partially alleviated by using higher-yielding late-maturing (130 CRM) cultivars. These cultivars demonstrated smaller yield reductions caused by film use than earlier-maturing cultivars (100 CRM), and were generally higher yielding ($p < 0.001$) (Figure 7.4; Figure 7.5).

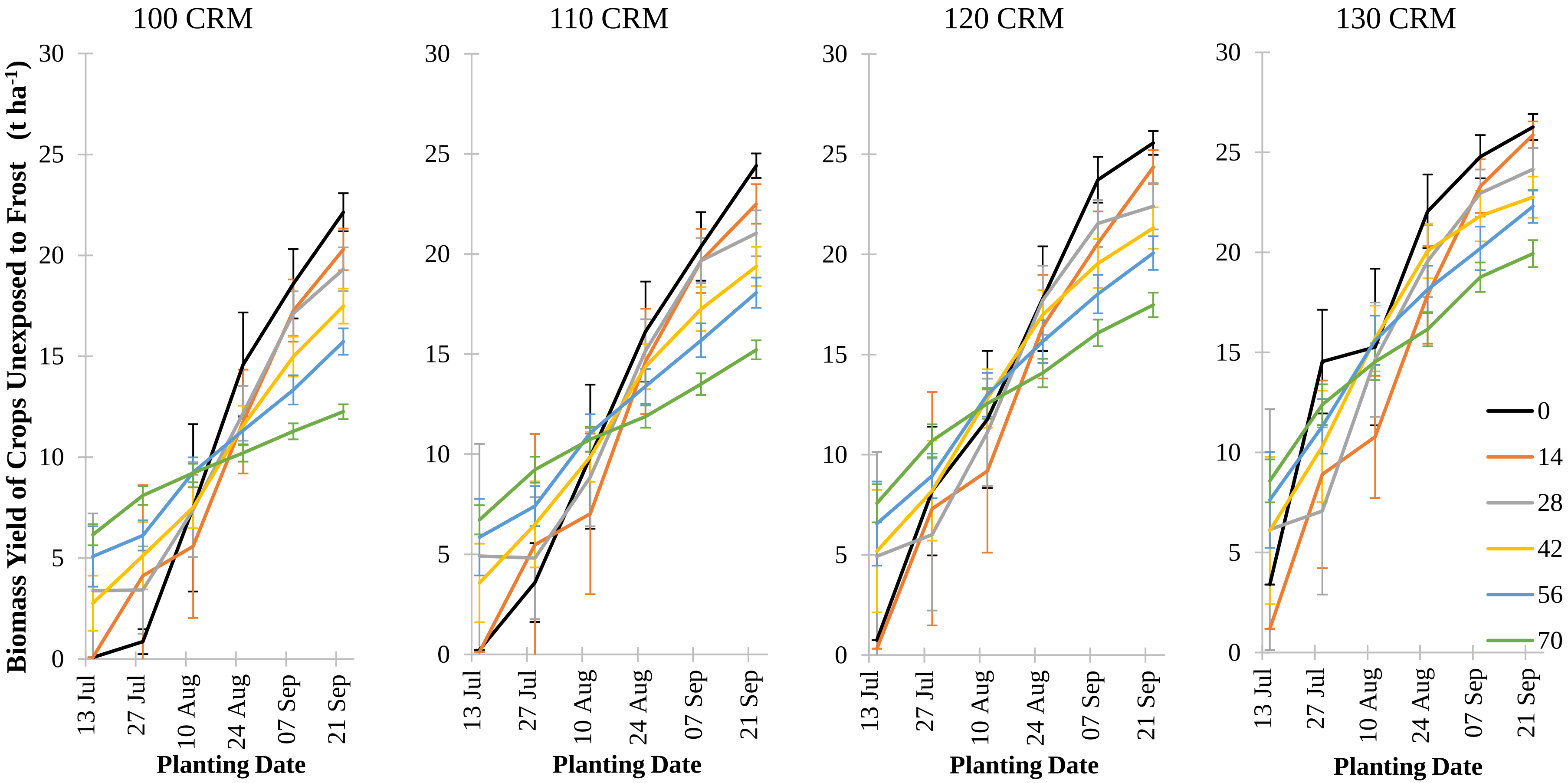

Figure 7.4 Mean harvested forage biomass produced by four cultivars with different comparative relative maturity (CRM) times using film-enclosed early planting systems at Bothwell, when sown between July 15th and September 23rd (x axis). The no. of days crops were grown in a film-enclosed environment is denoted by colour. Values represent mean ± SEM of crop simulations run between 1950-2015.

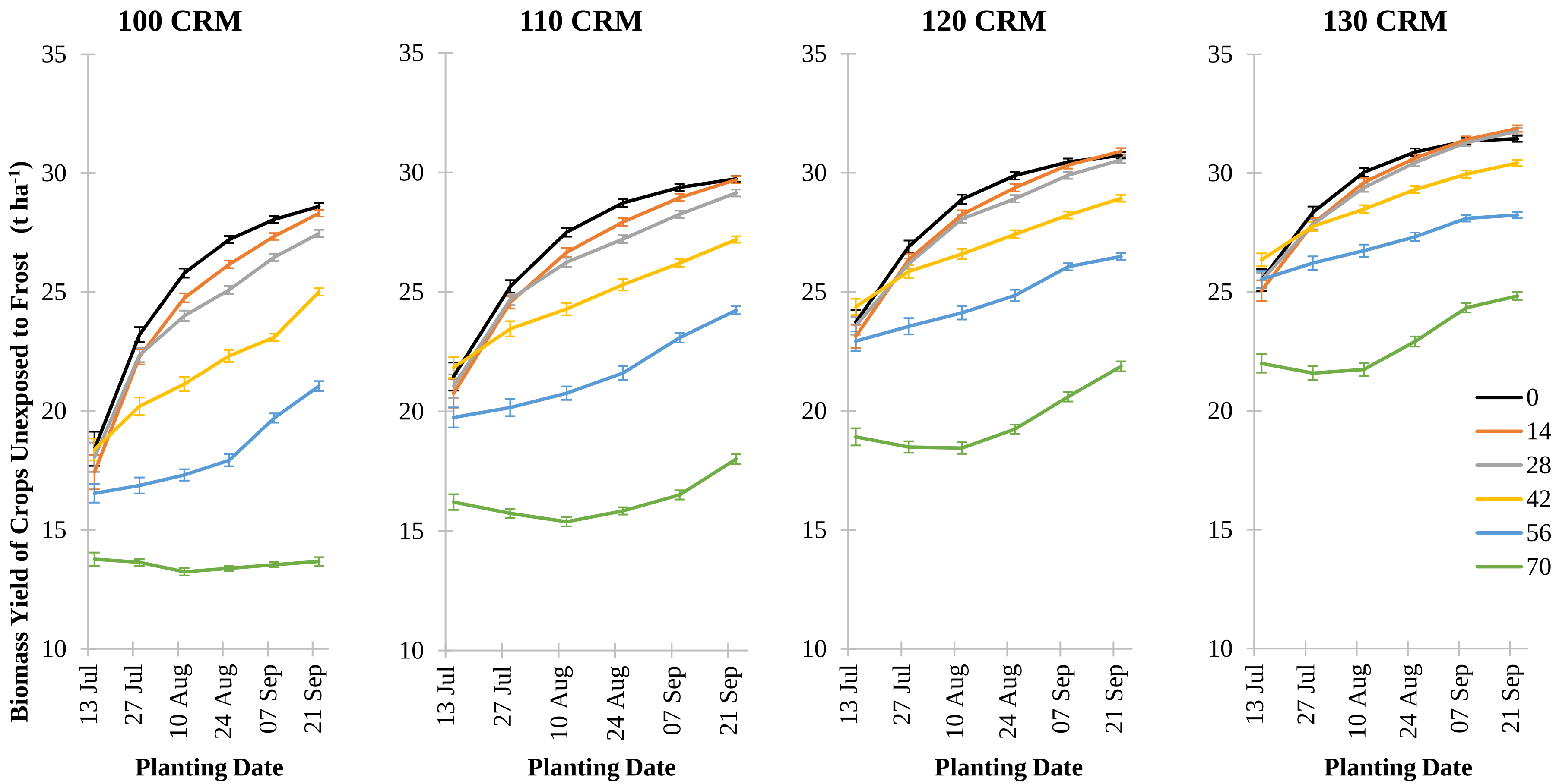

Figure 7.5 Mean harvested forage biomass produced by 4 cultivars with different comparative relative maturity (CRM) times using film-enclosed early planting systems at Devonport when sown between July 15th and September 23rd (x axis). The no. of days crops were grown in a film-enclosed environment is denoted by colour. Values represent mean ± SEM of crop simulations run between 1950-2015.

7.4.3 Crop Failure Rates

The use of film decreased crop failure risks in early-sown systems across all sites (Figure 7.6). Extended film use was associated with reduced rates of crop failure across all planting dates, with failure rates approaching 0 % at all sites if September planting dates were combined with prolonged film use. Rates of crop failure varied by site, with failure rates highest in Bothwell and Campbell Town, and lower at Elliott and Devonport (Figure 7.6). Crop failure rates of early-sown maize were influenced by crop planting date, cultivar CRM, and film duration at each site. Crop failure rates were lowest when planted during September and increased if planted before then (Figure 7.6). Cultivar CRM had mixed effects on crop failure rates; changes in cultivar CRM caused significant variations in crop failure rates in Bothwell and Campbell Town, but not in Devonport and Elliott (Figure 7.6).

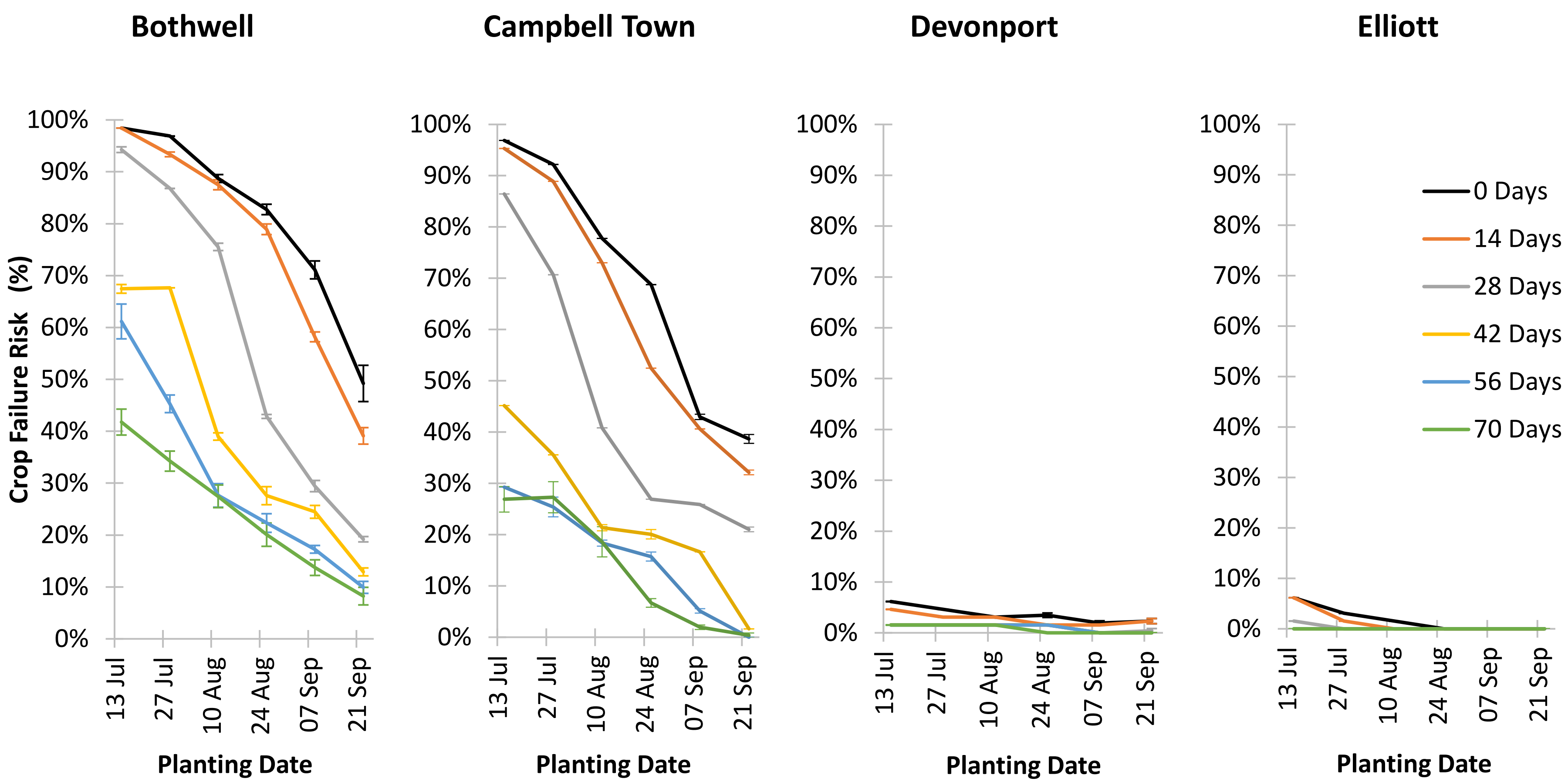

Figure 7.6 Mean crop failure risks for early-sown maize grown with (coloured) and without (black) film at four sites across Tasmania. The number of days crops were grown in a film-enclosed environment is denoted by colour. Values represent the mean failure rate ± SEM of four cultivars with different comparative relative maturity (CRM).

7.4.4 Long-term effects of film use

The long-term productivity effects of film use differed between inland and coastal regions. At the inland sites of Bothwell and Campbell Town, introduction of film into early-sowing systems increased long-term crop productivity. Maximum crop yields occurred when late-maturing (130 CRM) cultivars were planted on 23 September and protected by film for six weeks (Figure 7.7); using this combination, crops yielded 7-9 % more biomass than crops planted at these sites in accordance with existing recommendations (Figure 7.8). Film-based improvements in long-term productivity were associated with increases in the number of successfully harvested crops, due to earlier development, reduced cumulative frost exposure and decreased crop failure rates.

In contrast to inland regions, film use had mixed effects when used in Devonport and Elliott. Long-term biomass yields at these sites were largest when late-maturing cultivars (130 CRM) were planted on 23 September and enclosed by film for 14-28 days; using this combination, crops yielded 10-15 % more biomass than crops planted at these sites in accordance with existing recommendations (Figure 7.7). Cultivar CRM strongly influenced long-term crop yield responses to optimal film use at these sites, with optimal film use increasing biomass yields from late-maturing cultivars (130 CRM) by 0.67-0.84 t ha^{-1} and decreasing yields from earlier-maturing cultivars (100 CRM) by 0.53-1.11 t ha^{-1}. Film-based improvements in long-term productivity were associated with earlier crop development and reductions in cumulative frost exposure.

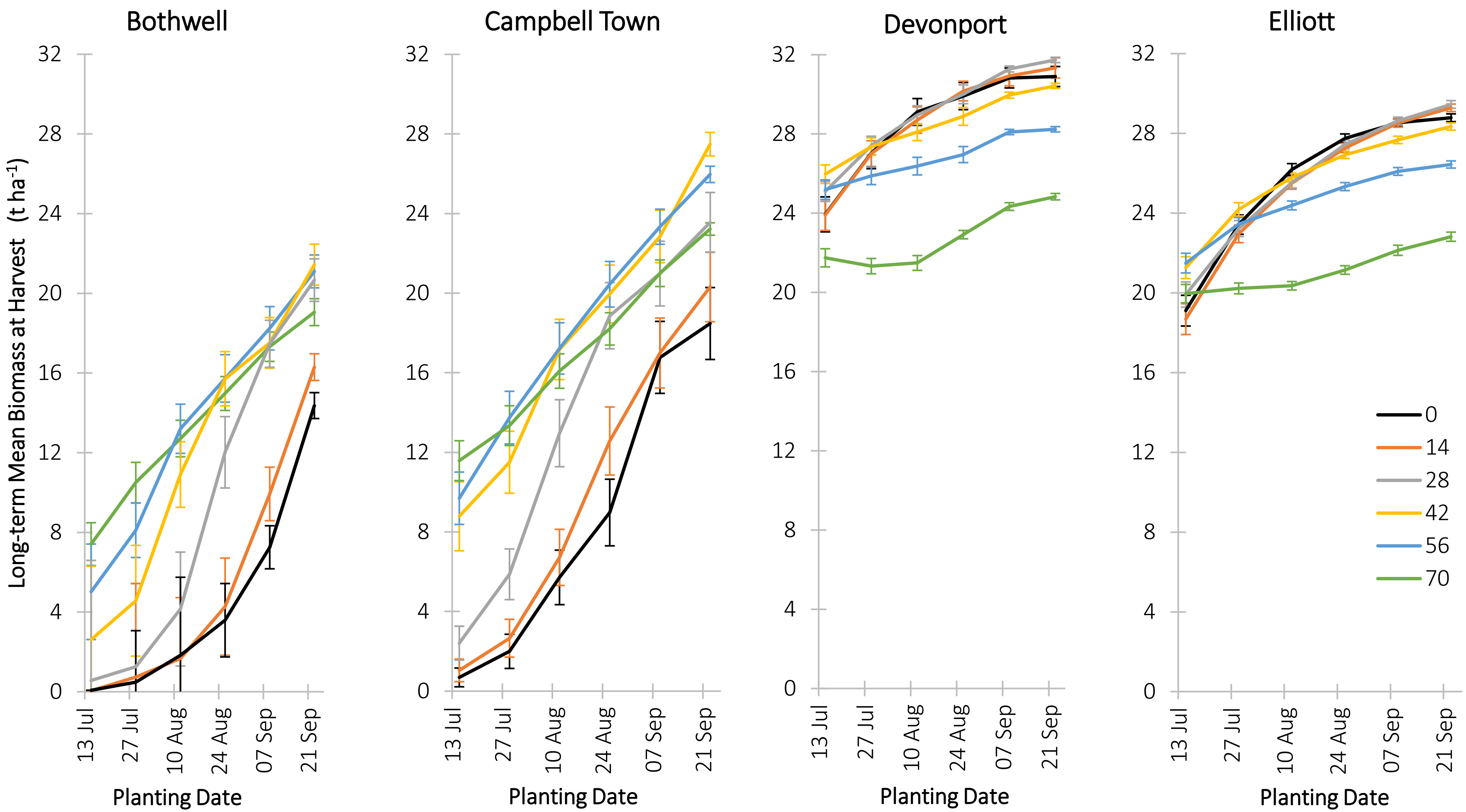

Figure 7.7 Mean harvested forage biomass harvested from a late-maturing cultivar (130 CRM) grown with (coloured) and without (black) film, when sown between 15 July and 23 September (x axis) at four sites across Tasmania. The number of days crops were grown in a film-enclosed environment is denoted by colour. Values represent mean ± the standard error of crop simulations run between 1950-2015.

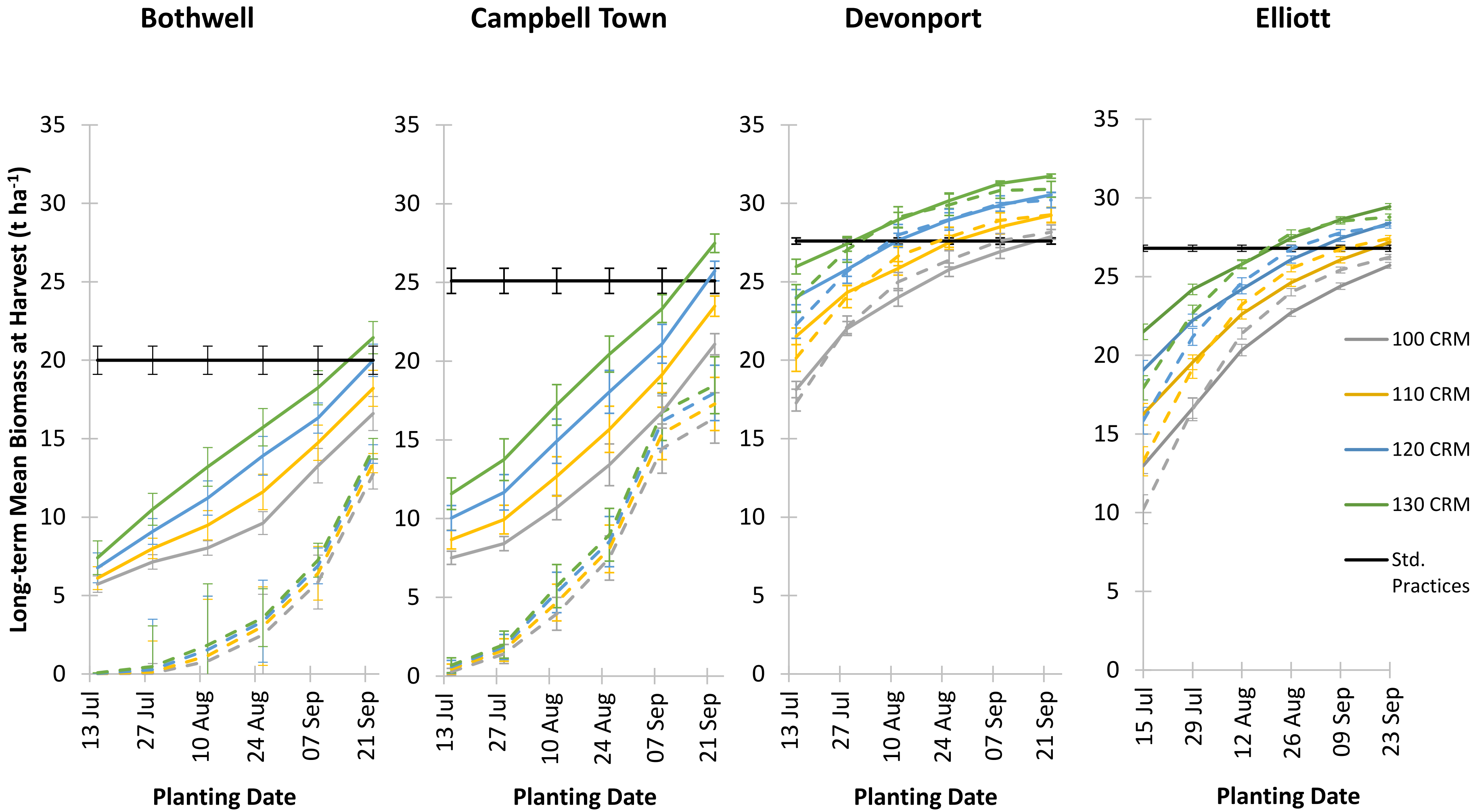

Figure 7.8 Harvested forage biomass produced by optimal film (solid line) and film-free (dotted line) early-sowing systems using four different cultivar CRMs. Values represent mean ± SEM of crop simulations run between 1950-2015.

7.5 Discussion

Film is being increasingly used for heat generation to support commercial maize production in cold-affected regions of China, Canada and Europe. In these regions, polymer film row covers act like a degradable glasshouse during the early stages of crop growth, trapping outgoing terrestrial radiation leading to increases in above- and below-ground temperatures (Miller and Bunger 1963; Courter *et al.,* 1969; Brown *et al.,* 1991; Aguyoh *et al.,* 1999; Keady 2001). Use of polymer film row covers in these areas has been demonstrated to enable earlier crop establishment (Crowley 1998), more efficient use of the longer summer days (Andrade *et al.,* 1993) and reduced risk from late frost events due to earlier maturation (e.g. sweet corn production in Newfoundland – Kwabiah 2003). This improves harvest productivity, reliability and profitability for maize producers (Manseur 1984).

In Chapter 3 it was shown that daily periods of acute heat stress experienced by crops under field conditions were likely to be significantly shorter and less severe than predicted by the APSIM model. Exposure of crops to air temperatures above 35 °C caused the APSIM model to decrease the efficiency of solar radiation conversion to plant biomass production by 6.7% $°C^{-1}$ above this threshold (Carberry *et al.*, 1989). Manual correction of these calculations (e.g. using Equation 3.1) is not possible within the APSIM framework, preventing more accurate temperature interpolation models from interacting with APSIM's maize and soil modules. This restriction prevents more accurate models being used to correct predictions of daily thermal time accumulation, extreme heat exposure, leaf area and senescence, solar radiation interception, biomass production, and solar radiation use efficiency. These issues mean that biomass yields from crops initially grown under film may be significantly higher than presented here.

With these caveats in place, the modelling presented shows that incorporating film use during seedling growth improved the resilience and reliability of early-sown forage maize production systems at frost-susceptible sites in inland Tasmania. Maize experiences physical damage to exposed leaf and stem tissues after being exposed to frost, and may experience complete crop failure in severe cases. As discussed in Chapter 6, this damage limits the productivity and reliability of forage maize production in inland regions of Tasmania, which are susceptible to frosts between early autumn and late spring (Australian Bureau of Meteorology, 2017). In these inland areas, it was shown that adoption of earlier planting dates protected by film enables crops to reach harvest maturity earlier, reducing crop exposure to autumn frosts. When used in this manner, film use reduced crop exposure to frost during early-spring planting dates and reduced crop exposure to autumn frosts in the high-frost sites of Bothwell and Campbell Town, improving rates of crop survival. Film enclosure during emergence and seedling growth greatly reduced crop failure rates at Bothwell from 41.5% to 8.2%. Similar reductions occurred at Campbell Town, where film use reduced crop failure rates from 15.4% to less than 1.6%. Without film use for frost protection, early-sowing practices were detrimental to crop survival and productivity at Bothwell and Campbell Town. Planting before 23 September caused estimated crop failure rates to increase from 15.4% to more than 38.7% in Campbell Town, due to crops being increasingly exposed to spring frosts. Similar increases occurred in Bothwell, with the failure rates of uncovered crops increasing from 49% to 83% when planted between mid-August and late September. This increase in the rate of crop failure reduced long-term crop yields at Campbell Town when planted between 26 August and 23 September, whilst yields from Bothwell decreased by approximately 0.3 t ha^{-1} day^{-1} throughout the same period.

Widespread adoption and use of film is likely to increase the long-term productivity of maize forage crops planted in Tasmania. Film use was beneficial in coastal sites like Devonport and Elliott, despite the low incidence of frost at these coastal sites. Long-term yields from film-protected crops planted throughout the late-August and September period were higher than crops planted using conventional practices. Increases in productivity at these sites may reflect faster crop development during spring, and increased leaf area and improved utilisation of incident solar radiation throughout summer and autumn. Increases in long-term productivity were even greater at the frost-susceptible sites of Bothwell and Campbell Town, where optimal film use increased long-term crop productivity by 7-10 t ha^{-1} across all planting dates. These increases reflect reductions in the rate of leaf abscission and crop failure caused by frost, ensuring crops continued growing efficiently until they reached harvest maturity. Forage maize crops sown had highest yields when planted during late September in both coastal and inland regions, with maximum benefits occurring when film enclosure was maintained for two-four weeks in coastal regions and four-six weeks in inland regions. Extending film use beyond this optimal period decreased biomass yields at harvest due to prolonged heat stress. Enclosure of crops after these periods was shown to decrease crop biomass productivity due to daily crop exposure to heat stress.

Adoption of film-protected early planting dates with late-maturing cultivars enabled forage maize to be successfully planted, grown and harvested earlier than is currently normal, effectively extending the potential maize growing season. This additional time enables growers of early-sown crops to safely adopt and safely grow later-maturing cultivars, which are more productive than earlier-maturing cultivars due to extended crop duration and increased opportunities for solar radiation interception, CO_2 assimilation, and biomass conversion. Having additional time also enables growers to consider replanting if crops become significantly affected by frost or other stresses during early growth, reducing some of the financial risks associated with earlier forage-planting dates. When incorporated into pasture-rotation or mixed-cropping systems, this earlier development provides additional time for producers to prepare and establish subsequent crops before the onset of winter (S. Bennet 2015, pers. comms; H. Mucha 2015, pers. comms).

Incorporation of film into maize production systems has several potential benefits in Tasmania. Film use has been demonstrated to increase seedling emergence, leaf development, leaf area and growth rates due to warmer temperatures favourable for maize growth under cold seasonal conditions (Chapter 5). Without film use, cold stress is a constant issue for maize producers in all regions of Tasmania, since average monthly temperatures are lower than the optimal temperature range (23-32 °C) for maize and other tropical crops (Mahan *et al.*, 1990). Under these cold seasonal conditions, film use increases leaf chlorophyll content, decreases chlorophyll bleaching caused by acute overnight chilling (Fracheboud *et al.*, 1999), and increases crop solar radiation use efficiency (Chapter 5). Without film use maize crops experience cold stress, reducing CO_2 fixation and growth rates (Leipner 2009) and causing leaves to become bleached of chlorophyll due to photoinhibition (Hetherington 1989; Lootens *et al.*, 2004). Prolonged cold stress can also stunt root growth and nutrient uptake, and slow leaf development and size. These issues decrease forage quality and crop productivity (St Pierre *et al.*, 1983; Riva-Roveda *et al.*, 2016) and delay crop forage maturity until 21-24 weeks after sowing (50 % milk line stage) (Chapter 6).

7.6 Conclusion

In existing coastal production regions the adoption of film-protected early planting dates enabled biomass yields to be increased by 10-15 % above existing practices by extending the effective growing system and enabling late-maturing cultivars to be safely grown. In inland Tasmania, the use of film-protected early planting dates increased crop productivity by 7-10

% over the long term and greatly reduced rates of crop failure caused by frost exposure. Reductions in crop productivity caused by heat stress were offset by increases in crop survival and growth to harvest maturity. These findings show that yields from film-enclosed systems can exceed the productivity and reliability levels likely to be achieved using production practices currently recommended in Tasmania.

Chapter 8: General Discussion

8.1 Introduction

This thesis evaluated the suitability of film for frost protection and environmental heating use in areas of Tasmania currently constrained by cold stress and seasonal frost. This evaluation was performed by identifying the daily and seasonal environmental changes caused by film use, including frost formation, soil and air temperatures, atmospheric composition, and solar radiation intensity. The physiological effects of these changes were then monitored in maize, a frost-sensitive model agricultural species with potential industry applications in Tasmania. These findings were incorporated into the APSIM crop modelling framework to estimate crop survival and yield effects over multiple seasons using historical weather records. In this chapter, the main findings of the studies undertaken with regards to the research objectives are summarised, and general conclusions described. Furthermore, in the context of findings presented, suggestions for future research in film applications are presented.

8.2 Frost Protection

Film is used in cold-affected regions to protect frost-sensitive species from cold and ice damage, with variable levels of success (Snyder and de Melo-Abreu, 2005; Orzolek 2017). Film use released latent heat into the enclosed headspace during vapour condensation, and slowed overall heat loss (Deltour *et al.*, 1985). During physiological experiments it was hypothesised (1) that film use would reduce frost formation within the enclosed headspace environment and decrease cereal damage from frost. After observing the absence of ice and frost damage in cereal seedlings grown under film-enclosed field conditions, it was postulated that film use avoided freezing-induced damage and cellular dehydration (Burke *et al.*, 1976; Pearce 2001). Maize was selected as an ideal test species due to its tolerance of high temperatures and high sensitivity to frost (Farooq *et al.*, 2009). Findings presented in Chapters 2, 3 and 6 supported the hypothesis, showing that maize seedlings grown under film were not susceptible to damage from frost and snow outside the film, and were not physically or physiologically damaged by exposure to sub-zero temperatures for short durations.

8.3 Effect of film on headspace temperature

To date, few studies have quantified the soil and air temperature changes caused by film use at different times of the year (Manera *et al.*, 1999; Crowley 1998) and its potential for soil solarisation (Katan *et al.*, 1976; Stapleton and DeVay, 1986). It was hypothesised (2) that heat created by film use would vary seasonally, with temperature increases smallest during the winter months and largest during summer. This hypothesis was supported by field observations carried out at Cambridge and Clifton Beach in Tasmania, which showed a modest temperature increase (5-10 °C above ambient) during winter but much larger temperature increases (30-35 °C) in spring and early summer. When coupled with concomitant increased ambient temperatures, these seasonal changes caused headspace temperatures to reach as high as 65 °C during summer.

It was also hypothesised (3) that soil water content would influence heat accumulation and storage within the film-enclosed headspace due to increased specific heat capacity and connectivity between particulates. In Chapter 2, it was shown that increasing soil moisture could reduce daily temperature fluctuations in the headspace environment by as much as 20 °C during late spring and early summer, due to increased minimum and decreased maximum temperatures. Soil moisture effects on headspace temperatures were less pronounced between late autumn and early spring, when increased shading from clouds and decreased day length and solar radiation intensity limited heat production.

Headspace temperature estimates presented in Chapter 3 showed that daily temperatures beneath the film were likely to cause increasingly severe heat stress in temperate crop species like wheat from August onwards. In tropical crops like maize, sorghum and cotton, headspace temperatures were unlikely to cause heat stress until October. It was hypothesised (4) that increased soil and air temperatures under film could enable earlier establishment of temperature-sensitive crops such as maize and improve seedling productivity in regions that experience cold stress. In Chapter 6 it was shown that warmer soil temperatures generated by film use increased seedling emergence rates and establishment percentages (90-95%) during July. Seedlings maintained higher concentrations of leaf chlorophyll, improving solar radiation capture and utilisation, and had faster rates of [CO_2] assimilation. These physiological benefits did not persist following removal of the film, with almost all physiological parameters adjusting to match seedlings grown without film within six days of film removal.

In Chapter 6 it was shown that improved maize physiology led to faster seedling growth and leaf area expansion. Film-enclosed seedlings exposed to higher headspace temperatures during daylight hours demonstrated few symptoms of cold stress, despite prolonged exposure to cold minimum temperatures (<5 °C). These observations suggest that cold-stress symptoms in maize are linked with photoinhibition, and plants are less sensitive to cold stress during periods of darkness. Seedlings grown beneath film did not elicit any symptoms of physiological shock caused by removal of the film enclosure, which caused air temperatures, vapour pressure deficits and atmospheric [CO_2] to decrease greatly. These results suggest that film use can reduce the sensitivity of maize and similar cold-sensitive tropical species to cold overnight temperatures, potentially allowing their commercial cultivation in Tasmania.

Hypothesis (5) was that seasonal increases in headspace temperature would cause seedlings to experience heat stress. In Chapter 6, exposure to heat stress caused leaf chlorophyll content to decrease, increased photoreceptor closure and reduced solar radiation use efficiency. Plants affected by these conditions subsequently demonstrated reduced rates of leaf [CO_2] assimilation and slower biomass production. In maize, these damaging effects occurred when maximum headspace temperatures exceeded 39 °C, with plants showing signs of recovery between heat stress events. In Chapter 3 it was shown that these temperature conditions occurred with increased frequency and severity under film throughout October and early November. In Chapter 7 it was shown that this decreased crop biomass production and yield at harvest.

The optimal timing of removal of film varied with location, depending on regional differences in the incidence of frost and heat stress. In inland regions of Tasmania, it was shown in Chapter 3 using a crop simulation model that the seasonal frost period overlaps with the periods of potentially fatal heat stress. In these regions, crops initially grown under film were still likely to be exposed to frost events after film removal or degradation, but there was demonstrated reduced crop failure from frost and improved long-term productivity when compared against simulations of existing production systems presented in Chapter 5. These results showed that film use could be beneficial in some areas when appropriate planting and degradation/removal dates could be implemented.

8.4 Effects on Headspace Atmosphere

Film installation has a significant effect on the gaseous composition of the enclosed headspace. The concentrations of these gases have been shown to influence leaf stomatal activity, carbon assimilation (Bunce, 2000), transpiration rates (Ball *et al.*, 1980), and evaporative cooling potential (Jones, 1992). Due to these effects, several studies were performed in Chapter 2 to better understand the diurnal and seasonal changes in headspace gas composition caused by film use.

Film use also creates complex changes in headspace [CO_2] within the enclosed headspace. Mao and Kurata (1997) showed using CO_2 tracer gas that the presence of film slowed the movement of [CO_2] between enclosed soil microflora and the wider environment. From this it was hypothesised (6) that the [CO_2] within the enclosed headspace would be much higher than ambient concentrations and would fluctuate due to changes in cellular respiration and photosynthetic assimilation rates. This hypothesis was strongly supported by headspace [CO_2] measurements in film-enclosed systems containing small unidentified weed seedlings, where [CO_2] fluctuated between 8-80 times the atmospheric [CO_2] concentrations in response to increased temperature and solar radiation. In control plots, headspace [CO_2] stabilised out between four-six times atmospheric [CO_2] concentrations, indicating that plant tissues were the primary consumer and producer of [CO_2] within the headspace environment. This has significant implications for crops with large areas of leaf biomass, which may cause headspace [CO_2] deficiency during periods of high solar radiation intensity, and hypoxia during periods of prolonged darkness. These issues will be less severe in slitted or perforated film systems, which trap [CO_2] less efficiently within the headspace environment and enable CO_2 to diffuse into the enclosed headspace if depleted.

Enrichment of headspace [CO_2] has been shown to have beneficial growth effects in plants that use the C_3 biochemical pathway photosynthetic carbon fixation (Kimball and Idso, 1983; Heins *et al.*, 1984; Idso *et al.*, 1987), but has mixed effects in plants using the C_4 pathway (Maroco *et al.*, 1999; Wand *et al.*, 1999; Ainsworth and Long, 2004). C_4 plants include several commercially important tropical grass species including maize, sorghum, sugarcane, and millet. Maize is the most intensively studied of these species and was used to test the hypothesis (7) that headspace [CO_2] within film-enclosed environments affects seedling photosynthesis, growth, and sensitivity to heat stress. Testing this hypothesis required the development and construction of small film-enclosed growing chambers described in Chapter 4, which automatically monitor and maintain [CO_2] near pre-set levels whilst maintaining the diurnal temperature and solar radiation fluctuations caused by film use. By developing and using these chambers it was shown that increased headspace [CO_2] above ambient levels caused no discernible changes in maize seedling emergence, establishment, biomass production or leaf area under film, and did not influence leaf [CO_2] assimilation rates, chlorophyll content, or solar radiation use efficiency, consistent with other authors (Ainsworth and Long, 2004; Kim *et al.*, 2007). These findings also suggest increased [CO_2] does not suppress stomatal activity and transpiration of maize and other C_4 grass species, which may increase the susceptibility of these plants to heat stress under film.

By contrast, plants using the C_3 pathway demonstrate faster rates of [CO_2] assimilation and biomass production in response to elevated headspace [CO_2]. Many common agricultural crops and weed species use this C_3 pathway, which may cause them to experience faster seedling growth and development rates (Kimball and Idso, 1983; Bowes 1993). Faster growth of these unwanted plant species is likely to increase interspecies competition for water, solar radiation, and soil nutrient resources within the enclosed growing environment, slowing resource accumulation and crop growth. Increased [CO_2] has also been linked to increased herbicide tolerance in weed species (Ziska *et al.*, 2004). There is some evidence to suggest that the efficacy of some herbicides may be reduced within film-enclosed environments (Mahan *et al.*, 2004). These effects may reduce the efficacy of pre-emergent herbicides used for early weed suppression in film systems. This may have implications for pest management strategies and favour the use of seed reduction using stale seedbed and soil solarisation techniques (Singh *et al.*, 2007; Gamliel and Katan, 2012).

One objective of experiments in Chapter 2 was to gain an understanding of how film use influences humidity and vapour pressure deficits under different seasonal conditions. Film use has previously been shown to cause water vapour to be retained within the enclosed headspace environment, increasing the water vapour content pressure and relative humidity of air (Moreno *et al.*, 2003; Olmstead and Tarara, 2001). Due to this vapour conservation mechanism it was hypothesised (8) that relative humidity would generally be higher within the enclosed headspace environment. This hypothesis was supported by field observations which showed that the maximum relative humidity of air within the enclosed headspace reaches saturation (100 % RH) at night, and that the minimum relative humidity during the day was usually higher in film-enclosed headspaces than under ambient conditions. Although maize has not been shown to be sensitive to prolonged exposure to high humidity, film use with more sensitive high-value tropical crops including tomatoes and cucumbers may cause metabolic disorders and physical blemishes (Holder and Cockshull, 2015; Barker *et al.*, 1987). Prolonged exposure to high relative humidity may also increase germination, infection and transmission of bacterial and fungal pathogens, increasing the susceptibility of crops to air- and soil-borne fungal and bacterial pathogens (Agrios, 2015).

Daily fluctuations in headspace relative humidity showed that air was not constantly saturated with vapour within the enclosed headspace, creating a deficit of water vapour pressure. It was hypothesised (9) that maximum daily vapour pressure deficits (VPD) would be similar to or greater than those occurring under ambient conditions due to the increased magnitude of temperature fluctuations. This hypothesis was supported by the data presented in Chapter 2, which showed that large vapour pressure deficits formed early each day before disappearing once the headspace started to cool. Maximum daily VPDs during this period varied in response to seasonal changes in solar radiation intensity, duration and ambient temperature, reaching a seasonal maximum of 15.1 kPa during mid-summer. Such extreme VPDs in the headspace environment rarely occur under ambient conditions and plant physiological responses, so have not been extensively studied in the literature. In maize and other model species, high VPD exposure (>2 kPa) increased rates of transpiration from aerial leaf tissues, increasing rates of latent heat loss and providing a measure of physiological protection from high temperature exposure (Seginer 1994; Costa *et al.*, 2013). Air saturation with water vapour indicates that potential transpiration rates will slow or cease during afternoon cooling events, limiting evaporative cooling as the enclosed headspace cools down. Exposure to high VPDs also reduced stomatal activity (to limit excessive water loss), thus decreasing rates of gas assimilation, photosynthesis and radiation-use efficiency during this period (Kinirya *et al.*, 1998). [CO_2] measurements presented in Chapter 2 showed that plants maintained some stomatal activity and gas assimilation throughout this period of extreme VPD, enabling continued photosynthesis.

8.5 Solar Radiation Effects

Solar radiation absorption is the primary driver of heat generation and plant growth within film-enclosed environments. Previous studies have measured optical transmission properties under field conditions, where transmission rates can be reduced by film curvature, condensation and dust. In Chapter 2 it was shown that under field conditions ~20 % of incident solar radiation was lost due to reflection and absorption, with another ~20 % scattered during instantaneous transmission measurements. Increases in solar radiation reflection and scattering were associated with condensation droplet formation on the under-side of the film. Soil type also influenced solar radiation transmission and absorption through the film, although the mechanism causing this effect remains uncertain. Although these factors reduce the availability of solar radiation for photosynthesis, they were observed to be less severe than reductions caused by heavy cloud cover and/or rain (up to ~ 80%). It was hypothesised (10) that instantaneous rates of solar radiation transmission and refraction would fluctuate during the day due to water droplet condensation and evaporation on the underside of the film. From this, it was further hypothesised (11) that solar radiation transmission rates would be greatest during summer when headspace conditions are most desiccating. Solar radiation transmission trends across all sites and soil types did not support hypotheses (10) or (11), with instantaneous and day-long measurements of solar radiation transmission rates remaining constant throughout the year-long trial despite daily oscillations in temperature, VPD, and visible fluctuations in condensation mass and volume.

Reductions in solar radiation transmission rates affect the physiology and development of maize. In Chapter 6 it was shown that cold-sensitive maize seedlings grown under reduced solar radiation intensity and rapidly warming conditions manifested fewer symptoms of cold damage and photoinhibition. When growing under high irradiance levels, these seedlings demonstrated only small increases in CO_2 assimilation rates. It was also shown in Chapter 3 that reductions in solar radiation intensity decrease heat accumulation beneath the film, leading to less heat stress. These findings suggest that small reductions in solar radiation intensity associated with film use will not detrimentally influence seedling productivity under film.

8.6 Suitability of Biophysical Models

In this thesis, biophysical simulations were used to estimate the long-term effects of film use on maize survival and productivity to identify optimal strategies for incorporating film into existing Tasmanian production systems. In Chapter 3 the objective was to develop statistical models to enable estimation of air and soil temperatures and cumulative solar radiation exposure within film-enclosed environments using ambient temperature and solar radiation measurements. These parameters were used in the APSIM modelling platform to estimate seasonal climatic conditions under film at different agricultural sites across Tasmania using historical weather observations. One limitation to the accuracy of the biophysical simulations is the prediction of the impact of high temperature under film on crop growth. In Chapter 3 an alternative algorithm was presented to address temperature overestimation, but the software engineering required to incorporate this algorithm into APSIM was outside the scope of this thesis. The discrepancies between predicted and observed headspace temperatures may cause flowering and harvest dates to vary from simulated dates by a small number of days, and daily estimates of maize biomass production to be smaller and more conservative.

It was hypothesised (12) that film use would increase forage survival and long-term productivity in both inland and coastal regions in Tasmania due to increased photosynthesis and reduced frost damage. Simulation outputs from these models supported this hypothesis, indicating that optimal film use practices increased long-term crop productivity in all regions. In coastal regions, reductions in forage biomass yields from heat stress could be offset by using film to reduce crop exposure to frost, increasing long-term productivity in these regions without significantly increasing risks of frost damage. In inland regions, film use also increased the survival of maize in elevated inland regions by reducing maize exposure to autumnal frost. Reductions in frost exposure increased long-term yields exceeded long-term estimated forage biomass yields currently possible in inland regions using existing industry practices by 7-10 %.

8.7 Research Implications

Film use was also shown to be an effective tool for protecting frost-sensitive seedlings from frost exposure and damage. In severely frost-constrained regions of Tasmania, this protection can reduce crop damage and failure rates, and significantly improve long-term crop productivity when applied in elevated and inland regions, increasing the feasibility of growing frost-sensitive crops like maize in these areas.

At this stage, excessive heat accumulation stress precludes film use on temperate crops and makes film suitable only for tropical crops. Introducing perforations into the film system may enable heat accumulation and crop thermal stress beneath the film to be reduced, but further investigation is still needed to optimise this approach. Without these modifications, excessive heat accumulation and crop heat stress are likely to constrain crop productivity and yield in film-enclosed systems in Tasmania, and limit adoption of the technology.

Soil type also demonstrated an influence on solar radiation attenuation rates with the soils presented here attenuating between 32% and 52% of incident solar radiation exposure beneath the polymer row covers. These differences in solar radiation attenuation are likely to influence heat accumulation within the enclosed headspace and may be caused by variations in surface roughness and porosity, textural heterogeneity, albedo, bed orientation, structure and/or angle of inclination between the film surface and sun, although the precise mechanisms involved are uncertain at this point in time. Future research in this area should investigate the quantitative effects of these factors have on solar radiation attenuation and subsequent heat accymulation.

Chapter 9: General Conclusion

- Film use increased maximum daily temperatures within the film-growing environment. Film use increased minimum daily temperatures by ~4°C between late spring and early autumn, but reduced minimum daily temperatures during other months. Maximum daily temperatures beneath film varied seasonally in response to solar radiation intensity and cloud shading, increasing temperatures by as much as 10 °C above ambient temperatures during winter and 40 °C during summer. Film use also reduced the transmission of solar radiation into the headspace by 20 % and increased the concentration of water vapour and CO_2 within the film-enclosed headspace. Models of these environmental changes were developed from ambient climate data, and were incorporated into APSIM to estimate temperatures at other sites from historical climate data.

- Use of film was shown to improve all aspects of seedling performance under seasonal cold conditions. Increases in seedling chlorophyll content, CO_2 assimilation and solar radiation utilisation caused by film use had few persistent effects on maize seedling physiology following removal of the film enclosure. Film use also caused headspace [CO_2] to fluctuate within the enclosed growing environment, but this had minimal effect on maize physiology and growth. Film use was less beneficial under warmer conditions, causing seedlings to regularly experience acute heat stress when exposed to damaging supra-optimal headspace temperatures above 40 °C.

- Optimal film use was shown to increase simulated maize forage productivity above existing industry practices by 10-15 % in coastal regions. In inland regions, incorporation of film into early-sowing systems reduced maize exposure to frost and crop failure rates and increased long-term crop yields by 7-10 % above existing industry practices. Yields from film-supported production systems reported in this thesis represent conservative estimates only, and potential increases in yield productivity achieved through film use may exceed those reported in this thesis.

- Establishment of effective weed control systems is likely to be difficult in film-enclosed systems due to reduced weed management options.

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Appendix 1: APSIM Prenewmet & Manager Code for Film-enclosed Headspace Climate

```
!  film = 0
!
!    if (date_within('[date1], [date2]') = 1) then
!       film = 1
!       radn = radn2
!       maxt = maxt2
!       irrigat_tot = 0
!       if (mint2 < 2.0) then
!          mint = 2.0
!       else mint = mint2
!       endif
!
!       if (rain > 0.0) then
!          rain = 0.0
!       endif
!    endif

!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
!!!!!!!!!!!!  TEMPERATURE RANGES  !!!!!!!!!!!!!!!!
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
!
!  AMBIENT TEMPERATURES
!
   radn_ambient = radn
   maxt_ambient = maxt
   mint_ambient = mint
   t_ambient_range = maxt_ambient - mint_ambient
!
!  AMBIENT 3HR TEMPERATURE DISTRIBUTION
   t_ambient1 = mint_ambient + 0.97005 * t_ambient_range
   t_ambient2 = mint_ambient + 0.91025 * t_ambient_range
   t_ambient3 = mint_ambient + 0.77345 * t_ambient_range
   t_ambient4 = mint_ambient + 0.59145 * t_ambient_range
   t_ambient5 = mint_ambient + 0.39605 * t_ambient_range
   t_ambient6 = mint_ambient + 0.21905 * t_ambient_range
   t_ambient7 = mint_ambient + 0.09225 * t_ambient_range
   t_ambient8 = mint_ambient + 0.04745 * t_ambient_range
!
!  FILM TEMPERATURES
```

```
!
   radn_film = ((0.7034*radn_ambient)+(3.7529*day_length/24))-0.4759)
   maxt_film = ((0.9287*radn_ambient)+(0.9437*maxt_ambient)-(0.2610*mint_ambient)-
(0.0915*radn_ambient)+(45.82*(day_length/24))-13.19)
   mint_film = ((0.7486*mint_ambient)+(0.1147*maxt_ambient)+(15.32*(day_length/24))-
8.353)
   t_film_range = maxt_film - mint_film
   rain = 0.0
!
!  FILM 3HR TEMPERATURE DISTRIBUTION - APSIM MODEL
!      APSIM estimates 3hrly temperatures by fitting the following algorithm to daily
maximum and minimum temperatures:
!        t_diurnal_range = maxt - mint
!        t_deviation = t_diurnal_range*t_range_fraction
!        t_range_fraction = 0.921505 + 0.1140*(x)^1 - 0.0703*(x)^2 + 0.0053*(x)^3; where (x)
is an integer representing the 3hrly time-point
!        temp3hr = t_deviation + tmin
!      to simplify this, I have already completed the multiplication step for t_range_fraction
!
!  To replicate this, I have created the variable t_APSIM#, where # represents the interger
representing the 3hrly timepoint
!     I have also redirected it to use maximum and minimum temperatures from beneath film
!
   t_APSIM_film1 = mint_film + 0.97005 * t_film_range
   t_APSIM_film2 = mint_film + 0.91025 * t_film_range
   t_APSIM_film3 = mint_film + 0.77345 * t_film_range
   t_APSIM_film4 = mint_film + 0.59145 * t_film_range
   t_APSIM_film5 = mint_film + 0.39605 * t_film_range
   t_APSIM_film6 = mint_film + 0.21905 * t_film_range
   t_APSIM_film7 = mint_film + 0.09225 * t_film_range
   t_APSIM_film8 = mint_film + 0.04745 * t_film_range
!
!  FILM 3HR TEMPERATURE DISTRIBUTION - STATISTICAL MODEL
!     The statistical model presented in Chapter 3 estimates 3hrly temperatures by fitting the
following algorithm:
!     temp3r = 1.011926*mint + 1.484743*t_diff - (0.559607*t_diff*sqrt(x)) +
sqrt(x)*1.155245
!     To simplify this, I have already calculated square roots for the values and factorised
!
t_stats_film1 = 1.011926*mint_film + 0.925136 * t_film_range + 1.155245
t_stats_film2 = 1.011926*mint_film + 0.693339 * t_film_range + 1.633763
t_stats_film3 = 1.011926*mint_film + 0.515475 * t_film_range + 2.000943
t_stats_film4 = 1.011926*mint_film + 0.365529 * t_film_range + 2.310490
t_stats_film5 = 1.011926*mint_film + 0.233424 * t_film_range + 2.583206
```

```
t_stats_film6 = 1.011926*mint_film + 0.113991 * t_film_range + 2.829761
t_stats_film7 = 1.011926*mint_film + 0.004162 * t_film_range + 3.056491
t_stats_film8 = 1.011926*mint_film - 0.098065 * t_film_range + 3.267526
!
!
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
!!!!!!!!!!!!!!!!!!!!!!  MAIZE THERMAL TIME  !!!!!!!!!!!!!!!!!!!!!!!!!!
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
!
!  MAIZE UNDER AMBIENT TEMPERATURES
!
!     AMBIENT 3HR INTERVAL # 1

      if t_ambient1 > 44 then
        tt_maize_ambient1 = 0
      endif

      if t_ambient1 >= 34 AND t_ambient1 < 44 then
        tt_maize_ambient1 = 26 + -2.6 * (t_ambient1 - 34)
      endif

      if t_ambient1 >= 26 AND t_ambient1 < 34 then
        tt_maize_ambient1 = 18 + 1 * (t_ambient1 - 26)
      endif

      if t_ambient1 >= 18 AND t_ambient1 < 26 then
        tt_maize_ambient1 = 10 + 1 * (t_ambient1 - 18)
      endif

      if t_ambient1 >= 0 AND t_ambient1 < 18 then
        tt_maize_ambient1 = 5 / 9 * t_ambient1
      endif

      if t_ambient1 <0 then
        tt_maize_ambient1 = 0
      endif

!     AMBIENT 3HR INTERVAL # 2
      if t_ambient2 > 44 then
        tt_maize_ambient2 = 0
      endif

      if t_ambient2 >= 34 AND t_ambient2 < 44 then
        tt_maize_ambient2 = 26 + -2.6 * (t_ambient2 - 34)
```

```
      endif

      if t_ambient2 >= 26 AND t_ambient2 < 34 then
        tt_maize_ambient2 = 18 + 1 * (t_ambient2 - 26)
      endif

      if t_ambient2 >= 18 AND t_ambient2 < 26 then
        tt_maize_ambient2 = 10 + 1 * (t_ambient2 - 18)
      endif

      if t_ambient2 >= 0 AND t_ambient2 < 18 then
        tt_maize_ambient2 = 5 / 9 * t_ambient2
      endif

      if t_ambient2 <0 then
        tt_maize_ambient2 = 0
      endif

!     AMBIENT 3HR INTERVAL # 3
      if t_ambient3 > 44 then
        tt_maize_ambient3 = 0
      endif

      if t_ambient3 >= 34 AND t_ambient3 < 44 then
        tt_maize_ambient3 = 26 + -2.6 * (t_ambient3 - 34)
      endif

      if t_ambient3 >= 26 AND t_ambient3 < 34 then
        tt_maize_ambient3 = 18 + 1 * (t_ambient3 - 26)
      endif

      if t_ambient3 >= 18 AND t_ambient3 < 26 then
        tt_maize_ambient3 = 10 + 1 * (t_ambient3 - 18)
      endif

      if t_ambient3 >= 0 AND t_ambient3 < 18 then
        tt_maize_ambient3 = 5 / 9 * t_ambient3
      endif

      if t_ambient3 <0 then
        tt_maize_ambient3 = 0
      endif

!     AMBIENT 3HR INTERVAL # 4
```

```
if t_ambient4 > 44 then
  tt_maize_ambient4 = 0
endif

if t_ambient4 >= 34 AND t_ambient4 < 44 then
  tt_maize_ambient4 = 26 + -2.6 * (t_ambient4 - 34)
endif

if t_ambient4 >= 26 AND t_ambient4 < 34 then
  tt_maize_ambient4 = 18 + 1 * (t_ambient4 - 26)
endif

if t_ambient4 >= 18 AND t_ambient4 < 26 then
  tt_maize_ambient4 = 10 + 1 * (t_ambient4 - 18)
endif

if t_ambient4 >= 0 AND t_ambient4 < 18 then
  tt_maize_ambient4 = 5 / 9 * t_ambient4
endif

if t_ambient4 <0 then
  tt_maize_ambient4 = 0
endif

!     AMBIENT 3HR INTERVAL # 5
if t_ambient5 > 44 then
  tt_maize_ambient5 = 0
endif

if t_ambient5 >= 34 AND t_ambient5 < 44 then
  tt_maize_ambient5 = 26 + -2.6 * (t_ambient5 - 34)
endif

if t_ambient5 >= 26 AND t_ambient5 < 34 then
  tt_maize_ambient5 = 18 + 1 * (t_ambient5 - 26)
endif

if t_ambient5 >= 18 AND t_ambient5 < 26 then
  tt_maize_ambient5 = 10 + 1 * (t_ambient5 - 18)
endif

if t_ambient5 >= 0 AND t_ambient5 < 18 then
  tt_maize_ambient5 = 5 / 9 * t_ambient5
endif
```

```
    if t_ambient5 <0 then
      tt_maize_ambient5 = 0
    endif

!   AMBIENT 3HR INTERVAL # 6
    if t_ambient6 > 44 then
      tt_maize_ambient6 = 0
    endif

    if t_ambient6 >= 34 AND t_ambient6 < 44 then
      tt_maize_ambient6 = 26 + -2.6 * (t_ambient6 - 34)
    endif

    if t_ambient6 >= 26 AND t_ambient6 < 34 then
      tt_maize_ambient6 = 18 + 1 * (t_ambient6 - 26)
    endif

    if t_ambient6 >= 18 AND t_ambient6 < 26 then
      tt_maize_ambient6 = 10 + 1 * (t_ambient6 - 18)
    endif

    if t_ambient6 >= 0 AND t_ambient6 < 18 then
      tt_maize_ambient6 = 5 / 9 * t_ambient6
    endif

    if t_ambient6 <0 then
      tt_maize_ambient6 = 0
    endif

!   AMBIENT 3HR INTERVAL # 7
    if t_ambient7 > 44 then
      tt_maize_ambient7 = 0
    endif

    if t_ambient7 >= 34 AND t_ambient7 < 44 then
      tt_maize_ambient7 = 26 + -2.6 * (t_ambient7 - 34)
    endif

    if t_ambient7 >= 26 AND t_ambient7 < 34 then
      tt_maize_ambient7 = 18 + 1 * (t_ambient7 - 26)
    endif

    if t_ambient7 >= 18 AND t_ambient7 < 26 then
```

```
    tt_maize_ambient7 = 10 + 1 * (t_ambient7 - 18)
  endif

  if t_ambient7 >= 0 AND t_ambient7 < 18 then
    tt_maize_ambient7 = 5 / 9 * t_ambient7
  endif

  if t_ambient7 <0 then
    tt_maize_ambient7 = 0
  endif

!     AMBIENT 3HR INTERVAL # 8
  if t_ambient8 > 44 then
    tt_maize_ambient8 = 0
  endif

  if t_ambient8 >= 34 AND t_ambient8 < 44 then
    tt_maize_ambient8 = 26 + -2.6 * (t_ambient8 - 34)
  endif

  if t_ambient8 >= 26 AND t_ambient8 < 34 then
    tt_maize_ambient8 = 18 + 1 * (t_ambient8 - 26)
  endif

  if t_ambient8 >= 18 AND t_ambient8 < 26 then
    tt_maize_ambient8 = 10 + 1 * (t_ambient8 - 18)
  endif

  if t_ambient8 >= 0 AND t_ambient8 < 18 then
    tt_maize_ambient8 = 5 / 9 * t_ambient8
  endif

  if t_ambient8 <0 then
    tt_maize_ambient8 = 0
  endif


  tt_maize_ambient_average = (tt_maize_ambient1 + tt_maize_ambient2 +
tt_maize_ambient3 + tt_maize_ambient4 + tt_maize_ambient5 + tt_maize_ambient6 +
tt_maize_ambient7 + tt_maize_ambient8) / 8
!
!
!  MAIZE UNDER FILM CONDITIONS - APSIM MODEL
!
```

```
!     FILM 3HR INTERVAL # 1

      if t_APSIM_film1 > 44 then
        tt_maize_APSIM_film1 = 0
      endif

      if t_APSIM_film1 >= 34 AND t_APSIM_film1 < 44 then
        tt_maize_APSIM_film1 = 26 + -2.6 * (t_APSIM_film1 - 34)
      endif

      if t_APSIM_film1 >= 26 AND t_APSIM_film1 < 34 then
        tt_maize_APSIM_film1 = 18 + 1 * (t_APSIM_film1 - 26)
      endif

      if t_APSIM_film1 >= 18 AND t_APSIM_film1 < 26 then
        tt_maize_APSIM_film1 = 10 + 1 * (t_APSIM_film1 - 18)
      endif

      if t_APSIM_film1 >= 0 AND t_APSIM_film1 < 18 then
        tt_maize_APSIM_film1 = 5 / 9 * t_APSIM_film1
      endif

      if t_APSIM_film1 <0 then
        tt_maize_APSIM_film1 = 0
      endif

!     FILM 3HR INTERVAL # 2
      if t_APSIM_film2 > 44 then
        tt_maize_APSIM_film2 = 0
      endif

      if t_APSIM_film2 >= 34 AND t_APSIM_film2 < 44 then
        tt_maize_APSIM_film2 = 26 + -2.6 * (t_APSIM_film2 - 34)
      endif

      if t_APSIM_film2 >= 26 AND t_APSIM_film2 < 34 then
        tt_maize_APSIM_film2 = 18 + 1 * (t_APSIM_film2 - 26)
      endif

      if t_APSIM_film2 >= 18 AND t_APSIM_film2 < 26 then
        tt_maize_APSIM_film2 = 10 + 1 * (t_APSIM_film2 - 18)
      endif

      if t_APSIM_film2 >= 0 AND t_APSIM_film2 < 18 then
```

```
      tt_maize_APSIM_film2 = 5 / 9 * t_APSIM_film2
    endif

    if t_APSIM_film2 <0 then
      tt_maize_APSIM_film2 = 0
    endif

!   FILM 3HR INTERVAL # 3
    if t_APSIM_film3 > 44 then
      tt_maize_APSIM_film3 = 0
    endif

    if t_APSIM_film3 >= 34 AND t_APSIM_film3 < 44 then
      tt_maize_APSIM_film3 = 26 + -2.6 * (t_APSIM_film3 - 34)
    endif

    if t_APSIM_film3 >= 26 AND t_APSIM_film3 < 34 then
      tt_maize_APSIM_film3 = 18 + 1 * (t_APSIM_film3 - 26)
    endif

    if t_APSIM_film3 >= 18 AND t_APSIM_film3 < 26 then
      tt_maize_APSIM_film3 = 10 + 1 * (t_APSIM_film3 - 18)
    endif

    if t_APSIM_film3 >= 0 AND t_APSIM_film3 < 18 then
      tt_maize_APSIM_film3 = 5 / 9 * t_APSIM_film3
    endif

    if t_APSIM_film3 <0 then
      tt_maize_APSIM_film3 = 0
    endif

!   FILM 3HR INTERVAL # 4
    if t_APSIM_film4 > 44 then
      tt_maize_APSIM_film4 = 0
    endif

    if t_APSIM_film4 >= 34 AND t_APSIM_film4 < 44 then
      tt_maize_APSIM_film4 = 26 + -2.6 * (t_APSIM_film4 - 34)
    endif

    if t_APSIM_film4 >= 26 AND t_APSIM_film4 < 34 then
      tt_maize_APSIM_film4 = 18 + 1 * (t_APSIM_film4 - 26)
    endif
```

```
    if t_APSIM_film4 >= 18 AND t_APSIM_film4 < 26 then
      tt_maize_APSIM_film4 = 10 + 1 * (t_APSIM_film4 - 18)
    endif

    if t_APSIM_film4 >= 0 AND t_APSIM_film4 < 18 then
      tt_maize_APSIM_film4 = 5 / 9 * t_APSIM_film4
    endif

    if t_APSIM_film4 <0 then
      tt_maize_APSIM_film4 = 0
    endif

!   FILM 3HR INTERVAL # 5
    if t_APSIM_film5 > 44 then
      tt_maize_APSIM_film5 = 0
    endif

    if t_APSIM_film5 >= 34 AND t_APSIM_film5 < 44 then
      tt_maize_APSIM_film5 = 26 + -2.6 * (t_APSIM_film5 - 34)
    endif

    if t_APSIM_film5 >= 26 AND t_APSIM_film5 < 34 then
      tt_maize_APSIM_film5 = 18 + 1 * (t_APSIM_film5 - 26)
    endif

    if t_APSIM_film5 >= 18 AND t_APSIM_film5 < 26 then
      tt_maize_APSIM_film5 = 10 + 1 * (t_APSIM_film5 - 18)
    endif

    if t_APSIM_film5 >= 0 AND t_APSIM_film5 < 18 then
      tt_maize_APSIM_film5 = 5 / 9 * t_APSIM_film5
    endif

    if t_APSIM_film5 <0 then
      tt_maize_APSIM_film5 = 0
    endif

!   FILM 3HR INTERVAL # 6
    if t_APSIM_film6 > 44 then
      tt_maize_APSIM_film6 = 0
    endif

    if t_APSIM_film6 >= 34 AND t_APSIM_film6 < 44 then
```

```
    tt_maize_APSIM_film6 = 26 + -2.6 * (t_APSIM_film6 - 34)
  endif

  if t_APSIM_film6 >= 26 AND t_APSIM_film6 < 34 then
    tt_maize_APSIM_film6 = 18 + 1 * (t_APSIM_film6 - 26)
  endif

  if t_APSIM_film6 >= 18 AND t_APSIM_film6 < 26 then
    tt_maize_APSIM_film6 = 10 + 1 * (t_APSIM_film6 - 18)
  endif

  if t_APSIM_film6 >= 0 AND t_APSIM_film6 < 18 then
    tt_maize_APSIM_film6 = 5 / 9 * t_APSIM_film6
  endif

  if t_APSIM_film6 <0 then
    tt_maize_APSIM_film6 = 0
  endif

!   FILM 3HR INTERVAL # 7
  if t_APSIM_film7 > 44 then
    tt_maize_APSIM_film7 = 0
  endif

  if t_APSIM_film7 >= 34 AND t_APSIM_film7 < 44 then
    tt_maize_APSIM_film7 = 26 + -2.6 * (t_APSIM_film7 - 34)
  endif

  if t_APSIM_film7 >= 26 AND t_APSIM_film7 < 34 then
    tt_maize_APSIM_film7 = 18 + 1 * (t_APSIM_film7 - 26)
  endif

  if t_APSIM_film7 >= 18 AND t_APSIM_film7 < 26 then
    tt_maize_APSIM_film7 = 10 + 1 * (t_APSIM_film7 - 18)
  endif

  if t_APSIM_film7 >= 0 AND t_APSIM_film7 < 18 then
    tt_maize_APSIM_film7 = 5 / 9 * t_APSIM_film7
  endif

  if t_APSIM_film7 <0 then
    tt_maize_APSIM_film7 = 0
  endif
```

```
!     FILM 3HR INTERVAL # 8
      if t_APSIM_film8 > 44 then
        tt_maize_APSIM_film8 = 0
      endif

      if t_APSIM_film8 >= 34 AND t_APSIM_film8 < 44 then
        tt_maize_APSIM_film8 = 26 + -2.6 * (t_APSIM_film8 - 34)
      endif

      if t_APSIM_film8 >= 26 AND t_APSIM_film8 < 34 then
        tt_maize_APSIM_film8 = 18 + 1 * (t_APSIM_film8 - 26)
      endif

      if t_APSIM_film8 >= 18 AND t_APSIM_film8 < 26 then
        tt_maize_APSIM_film8 = 10 + 1 * (t_APSIM_film8 - 18)
      endif

      if t_APSIM_film8 >= 0 AND t_APSIM_film8 < 18 then
        tt_maize_APSIM_film8 = 5 / 9 * t_APSIM_film8
      endif

      if t_APSIM_film8 <0 then
        tt_maize_APSIM_film8 = 0
      endif


      tt_maize_APSIM_film_average = (tt_maize_APSIM_film1 + tt_maize_APSIM_film2 +
tt_maize_APSIM_film3 + tt_maize_APSIM_film4 + tt_maize_APSIM_film5 +
tt_maize_APSIM_film6 + tt_maize_APSIM_film7 + tt_maize_APSIM_film8) / 8


!  MAIZE UNDER FILM TEMPERATURES - STATISTICAL MODEL
!
!     FILM 3HR INTERVAL # 1

      if t_stats_film1 > 44 then
        tt_maize_stats_film1 = 0
      endif

      if t_stats_film1 >= 34 AND t_stats_film1 < 44 then
        tt_maize_stats_film1 = 26 + -2.6 * (t_stats_film1 - 34)
      endif

      if t_stats_film1 >= 26 AND t_stats_film1 < 34 then
```

```
    tt_maize_stats_film1 = 18 + 1 * (t_stats_film1 - 26)
  endif

  if t_stats_film1 >= 18 AND t_stats_film1 < 26 then
    tt_maize_stats_film1 = 10 + 1 * (t_stats_film1 - 18)
  endif

  if t_stats_film1 >= 0 AND t_stats_film1 < 18 then
    tt_maize_stats_film1 = 5 / 9 * t_stats_film1
  endif

  if t_stats_film1 <0 then
    tt_maize_stats_film1 = 0
  endif

!     FILM 3HR INTERVAL # 2
  if t_stats_film2 > 44 then
    tt_maize_stats_film2 = 0
  endif

  if t_stats_film2 >= 34 AND t_stats_film2 < 44 then
    tt_maize_stats_film2 = 26 + -2.6 * (t_stats_film2 - 34)
  endif

  if t_stats_film2 >= 26 AND t_stats_film2 < 34 then
    tt_maize_stats_film2 = 18 + 1 * (t_stats_film2 - 26)
  endif

  if t_stats_film2 >= 18 AND t_stats_film2 < 26 then
    tt_maize_stats_film2 = 10 + 1 * (t_stats_film2 - 18)
  endif

  if t_stats_film2 >= 0 AND t_stats_film2 < 18 then
    tt_maize_stats_film2 = 5 / 9 * t_stats_film2
  endif

  if t_stats_film2 <0 then
    tt_maize_stats_film2 = 0
  endif

!     FILM 3HR INTERVAL # 3
  if t_stats_film3 > 44 then
    tt_maize_stats_film3 = 0
  endif
```

```
    if t_stats_film3 >= 34 AND t_stats_film3 < 44 then
      tt_maize_stats_film3 = 26 + -2.6 * (t_stats_film3 - 34)
    endif

    if t_stats_film3 >= 26 AND t_stats_film3 < 34 then
      tt_maize_stats_film3 = 18 + 1 * (t_stats_film3 - 26)
    endif

    if t_stats_film3 >= 18 AND t_stats_film3 < 26 then
      tt_maize_stats_film3 = 10 + 1 * (t_stats_film3 - 18)
    endif

    if t_stats_film3 >= 0 AND t_stats_film3 < 18 then
      tt_maize_stats_film3 = 5 / 9 * t_stats_film3
    endif

    if t_stats_film3 <0 then
      tt_maize_stats_film3 = 0
    endif

!   FILM 3HR INTERVAL # 4
    if t_stats_film4 > 44 then
      tt_maize_stats_film4 = 0
    endif

    if t_stats_film4 >= 34 AND t_stats_film4 < 44 then
      tt_maize_stats_film4 = 26 + -2.6 * (t_stats_film4 - 34)
    endif

    if t_stats_film4 >= 26 AND t_stats_film4 < 34 then
      tt_maize_stats_film4 = 18 + 1 * (t_stats_film4 - 26)
    endif

    if t_stats_film4 >= 18 AND t_stats_film4 < 26 then
      tt_maize_stats_film4 = 10 + 1 * (t_stats_film4 - 18)
    endif

    if t_stats_film4 >= 0 AND t_stats_film4 < 18 then
      tt_maize_stats_film4 = 5 / 9 * t_stats_film4
    endif

    if t_stats_film4 <0 then
      tt_maize_stats_film4 = 0
```

```
    endif

!   FILM 3HR INTERVAL # 5
    if t_stats_film5 > 44 then
      tt_maize_stats_film5 = 0
    endif

    if t_stats_film5 >= 34 AND t_stats_film5 < 44 then
      tt_maize_stats_film5 = 26 + -2.6 * (t_stats_film5 - 34)
    endif

    if t_stats_film5 >= 26 AND t_stats_film5 < 34 then
      tt_maize_stats_film5 = 18 + 1 * (t_stats_film5 - 26)
    endif

    if t_stats_film5 >= 18 AND t_stats_film5 < 26 then
      tt_maize_stats_film5 = 10 + 1 * (t_stats_film5 - 18)
    endif

    if t_stats_film5 >= 0 AND t_stats_film5 < 18 then
      tt_maize_stats_film5 = 5 / 9 * t_stats_film5
    endif

    if t_stats_film5 <0 then
      tt_maize_stats_film5 = 0
    endif

!   FILM 3HR INTERVAL # 6
    if t_stats_film6 > 44 then
      tt_maize_stats_film6 = 0
    endif

    if t_stats_film6 >= 34 AND t_stats_film6 < 44 then
      tt_maize_stats_film6 = 26 + -2.6 * (t_stats_film6 - 34)
    endif

    if t_stats_film6 >= 26 AND t_stats_film6 < 34 then
      tt_maize_stats_film6 = 18 + 1 * (t_stats_film6 - 26)
    endif

    if t_stats_film6 >= 18 AND t_stats_film6 < 26 then
      tt_maize_stats_film6 = 10 + 1 * (t_stats_film6 - 18)
    endif
```

```
    if t_stats_film6 >= 0 AND t_stats_film6 < 18 then
      tt_maize_stats_film6 = 5 / 9 * t_stats_film6
    endif

    if t_stats_film6 <0 then
      tt_maize_stats_film6 = 0
    endif

!   FILM 3HR INTERVAL # 7
    if t_stats_film7 > 44 then
      tt_maize_stats_film7 = 0
    endif

    if t_stats_film7 >= 34 AND t_stats_film7 < 44 then
      tt_maize_stats_film7 = 26 + -2.6 * (t_stats_film7 - 34)
    endif

    if t_stats_film7 >= 26 AND t_stats_film7 < 34 then
      tt_maize_stats_film7 = 18 + 1 * (t_stats_film7 - 26)
    endif

    if t_stats_film7 >= 18 AND t_stats_film7 < 26 then
      tt_maize_stats_film7 = 10 + 1 * (t_stats_film7 - 18)
    endif

    if t_stats_film7 >= 0 AND t_stats_film7 < 18 then
      tt_maize_stats_film7 = 5 / 9 * t_stats_film7
    endif

    if t_stats_film7 <0 then
      tt_maize_stats_film7 = 0
    endif

!   FILM 3HR INTERVAL # 8
    if t_stats_film8 > 44 then
      tt_maize_stats_film8 = 0
    endif

    if t_stats_film8 >= 34 AND t_stats_film8 < 44 then
      tt_maize_stats_film8 = 26 + -2.6 * (t_stats_film8 - 34)
    endif

    if t_stats_film8 >= 26 AND t_stats_film8 < 34 then
      tt_maize_stats_film8 = 18 + 1 * (t_stats_film8 - 26)
```

```
    endif

    if t_stats_film8 >= 18 AND t_stats_film8 < 26 then
      tt_maize_stats_film8 = 10 + 1 * (t_stats_film8 - 18)
    endif

    if t_stats_film8 >= 0 AND t_stats_film8 < 18 then
      tt_maize_stats_film8 = 5 / 9 * t_stats_film8
    endif

    if t_stats_film8 <0 then
      tt_maize_stats_film8 = 0
    endif


    tt_maize_stats_film_average = (tt_maize_stats_film1 + tt_maize_stats_film2 +
tt_maize_stats_film3 + tt_maize_stats_film4 + tt_maize_stats_film5 + tt_maize_stats_film6 +
tt_maize_stats_film7 + tt_maize_stats_film8) / 8

!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
!!!!!!!!!!!!!!!!!!!!!!  WHEAT THERMAL TIME  !!!!!!!!!!!!!!!!!!!!!!!!!!
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
!
!    AMBIENT 3HR INTERVAL # 1

    if t_ambient1 > 34 then
      tt_wheat_ambient1 = 0
    endif

    if t_ambient1 >= 26 AND t_ambient1 < 34 then
      tt_wheat_ambient1 = 26 + -3.25 * (t_ambient1 - 26)
    endif

    if t_ambient1 >= 0 AND t_ambient1 < 26 then
      tt_wheat_ambient1 = t_ambient1
    endif

    if t_ambient1 <0 then
      tt_wheat_ambient1 = 0
    endif

!    AMBIENT 3HR INTERVAL # 2

    if t_ambient2 > 34 then
```

```
    tt_wheat_ambient2 = 0
  endif

  if t_ambient2 >= 26 AND t_ambient2 < 34 then
    tt_wheat_ambient2 = 26 + -3.25 * (t_ambient2 - 26)
  endif

  if t_ambient2 >= 0 AND t_ambient2 < 26 then
    tt_wheat_ambient2 = t_ambient2
  endif

  if t_ambient2 <0 then
    tt_wheat_ambient2 = 0
  endif

!   AMBIENT 3HR INTERVAL # 3

  if t_ambient3 > 34 then
    tt_wheat_ambient3 = 0
  endif

  if t_ambient3 >= 26 AND t_ambient3 < 34 then
    tt_wheat_ambient3 = 26 + -3.25 * (t_ambient3 - 26)
  endif

  if t_ambient3 >= 0 AND t_ambient3 < 26 then
    tt_wheat_ambient3 = t_ambient3
  endif

  if t_ambient3 <0 then
    tt_wheat_ambient3 = 0
  endif

!   AMBIENT 3HR INTERVAL # 4

  if t_ambient4 > 34 then
    tt_wheat_ambient4 = 0
  endif

  if t_ambient4 >= 26 AND t_ambient4 < 34 then
    tt_wheat_ambient4 = 26 + -3.25 * (t_ambient4 - 26)
  endif

  if t_ambient4 >= 0 AND t_ambient4 < 26 then
```

```
      tt_wheat_ambient4 = t_ambient4
    endif

    if t_ambient4 <0 then
      tt_wheat_ambient4 = 0
    endif

!   AMBIENT 3HR INTERVAL # 5

    if t_ambient5 > 34 then
      tt_wheat_ambient5 = 0
    endif

    if t_ambient5 >= 26 AND t_ambient5 < 34 then
      tt_wheat_ambient5 = 26 + -3.25 * (t_ambient5 - 26)
    endif

    if t_ambient5 >= 0 AND t_ambient5 < 26 then
      tt_wheat_ambient5 = t_ambient5
    endif

    if t_ambient5 <0 then
      tt_wheat_ambient5 = 0
    endif

!   AMBIENT 3HR INTERVAL # 6

    if t_ambient6 > 34 then
      tt_wheat_ambient6 = 0
    endif

    if t_ambient6 >= 26 AND t_ambient6 < 34 then
      tt_wheat_ambient6 = 26 + -3.25 * (t_ambient6 - 26)
    endif

    if t_ambient6 >= 0 AND t_ambient6 < 26 then
      tt_wheat_ambient6 = t_ambient6
    endif

    if t_ambient6 <0 then
      tt_wheat_ambient6 = 0
    endif

!   AMBIENT 3HR INTERVAL # 7
```

```
      if t_ambient7 > 34 then
        tt_wheat_ambient7 = 0
      endif

      if t_ambient7 >= 26 AND t_ambient7 < 34 then
        tt_wheat_ambient7 = 26 + -3.25 * (t_ambient7 - 26)
      endif

      if t_ambient7 >= 0 AND t_ambient7 < 26 then
        tt_wheat_ambient7 = t_ambient7
      endif

      if t_ambient7 <0 then
        tt_wheat_ambient7 = 0
      endif

!     AMBIENT 3HR INTERVAL # 8

      if t_ambient8 > 34 then
        tt_wheat_ambient8 = 0
      endif

      if t_ambient8 >= 26 AND t_ambient8 < 34 then
        tt_wheat_ambient8 = 26 + -3.25 * (t_ambient8 - 26)
      endif

      if t_ambient8 >= 0 AND t_ambient8 < 26 then
        tt_wheat_ambient8 = t_ambient8
      endif

      if t_ambient8 <0 then
        tt_wheat_ambient8 = 0
      endif

      tt_wheat_ambient_average = (tt_wheat_ambient1 + tt_wheat_ambient2 +
tt_wheat_ambient3 + tt_wheat_ambient4 + tt_wheat_ambient5 + tt_wheat_ambient6 +
tt_wheat_ambient7 + tt_wheat_ambient8) / 8
!
!
!  WHEAT UNDER FILM TEMPERATURES – APSIM MODEL
!
!     FILM 3HR INTERVAL # 1
```

```
    if t_APSIM_film1 > 34 then
      tt_wheat_APSIM_film1 = 0
    endif

    if t_APSIM_film1 >= 26 AND t_APSIM_film1 < 34 then
      tt_wheat_APSIM_film1 = 26 + -3.25 * (t_APSIM_film1 - 26)
    endif

    if t_APSIM_film1 >= 0 AND t_APSIM_film1 < 26 then
      tt_wheat_APSIM_film1 = t_APSIM_film1
    endif

    if t_APSIM_film1 <0 then
      tt_wheat_APSIM_film1 = 0
    endif

!   FILM 3HR INTERVAL # 2

    if t_APSIM_film2 > 34 then
      tt_wheat_APSIM_film2 = 0
    endif

    if t_APSIM_film2 >= 26 AND t_APSIM_film2 < 34 then
      tt_wheat_APSIM_film2 = 26 + -3.25 * (t_APSIM_film2 - 26)
    endif

    if t_APSIM_film2 >= 0 AND t_APSIM_film2 < 26 then
      tt_wheat_APSIM_film2 = t_APSIM_film2
    endif

    if t_APSIM_film2 <0 then
      tt_wheat_APSIM_film2 = 0
    endif

!   FILM 3HR INTERVAL # 3

    if t_APSIM_film3 > 34 then
      tt_wheat_APSIM_film3 = 0
    endif

    if t_APSIM_film3 >= 26 AND t_APSIM_film3 < 34 then
      tt_wheat_APSIM_film3 = 26 + -3.25 * (t_APSIM_film3 - 26)
    endif
```

```
    if t_APSIM_film3 >= 0 AND t_APSIM_film3 < 26 then
      tt_wheat_APSIM_film3 = t_APSIM_film3
    endif

    if t_APSIM_film3 <0 then
      tt_wheat_APSIM_film3 = 0
    endif

!   FILM 3HR INTERVAL # 4

    if t_APSIM_film4 > 34 then
      tt_wheat_APSIM_film4 = 0
    endif

    if t_APSIM_film4 >= 26 AND t_APSIM_film4 < 34 then
      tt_wheat_APSIM_film4 = 26 + -3.25 * (t_APSIM_film4 - 26)
    endif

    if t_APSIM_film4 >= 0 AND t_APSIM_film4 < 26 then
      tt_wheat_APSIM_film4 = t_APSIM_film4
    endif

    if t_APSIM_film4 <0 then
      tt_wheat_APSIM_film4 = 0
    endif

!   FILM 3HR INTERVAL # 5

    if t_APSIM_film5 > 34 then
      tt_wheat_APSIM_film5 = 0
    endif

    if t_APSIM_film5 >= 26 AND t_APSIM_film5 < 34 then
      tt_wheat_APSIM_film5 = 26 + -3.25 * (t_APSIM_film5 - 26)
    endif

    if t_APSIM_film5 >= 0 AND t_APSIM_film5 < 26 then
      tt_wheat_APSIM_film5 = t_APSIM_film5
    endif

    if t_APSIM_film5 <0 then
      tt_wheat_APSIM_film5 = 0
    endif
```

```
!     FILM 3HR INTERVAL # 6

      if t_APSIM_film6 > 34 then
        tt_wheat_APSIM_film6 = 0
      endif

      if t_APSIM_film6 >= 26 AND t_APSIM_film6 < 34 then
        tt_wheat_APSIM_film6 = 26 + -3.25 * (t_APSIM_film6 - 26)
      endif

      if t_APSIM_film6 >= 0 AND t_APSIM_film6 < 26 then
        tt_wheat_APSIM_film6 = t_APSIM_film6
      endif

      if t_APSIM_film6 <0 then
        tt_wheat_APSIM_film6 = 0
      endif

!     FILM 3HR INTERVAL # 7

      if t_APSIM_film7 > 34 then
        tt_wheat_APSIM_film7 = 0
      endif

      if t_APSIM_film7 >= 26 AND t_APSIM_film7 < 34 then
        tt_wheat_APSIM_film7 = 26 + -3.25 * (t_APSIM_film7 - 26)
      endif

      if t_APSIM_film7 >= 0 AND t_APSIM_film7 < 26 then
        tt_wheat_APSIM_film7 = t_APSIM_film7
      endif

      if t_APSIM_film7 <0 then
        tt_wheat_APSIM_film7 = 0
      endif

!     FILM 3HR INTERVAL # 8

      if t_APSIM_film8 > 34 then
        tt_wheat_APSIM_film8 = 0
      endif

      if t_APSIM_film8 >= 26 AND t_APSIM_film8 < 34 then
        tt_wheat_APSIM_film8 = 26 + -3.25 * (t_APSIM_film8 - 26)
```

```
      endif

      if t_APSIM_film8 >= 0 AND t_APSIM_film8 < 26 then
        tt_wheat_APSIM_film8 = t_APSIM_film8
      endif

      if t_APSIM_film8 <0 then
        tt_wheat_APSIM_film8 = 0
      endif

      tt_wheat_APSIM_film_average = (tt_wheat_APSIM_film1 + tt_wheat_APSIM_film2 +
tt_wheat_APSIM_film3 + tt_wheat_APSIM_film4 + tt_wheat_APSIM_film5 +
tt_wheat_APSIM_film6 + tt_wheat_APSIM_film7 + tt_wheat_APSIM_film8) / 8
!
!
!  WHEAT UNDER FILM TEMPERATURES – STATISTICAL MODEL
!
!     FILM 3HR INTERVAL # 1

      if t_stats_film1 > 34 then
        tt_wheat_stats_film1 = 0
      endif

      if t_stats_film1 >= 26 AND t_stats_film1 < 34 then
        tt_wheat_stats_film1 = 26 + -3.25 * (t_stats_film1 - 26)
      endif

      if t_stats_film1 >= 0 AND t_stats_film1 < 26 then
        tt_wheat_stats_film1 = t_stats_film1
      endif

      if t_stats_film1 <0 then
        tt_wheat_stats_film1 = 0
      endif

!     FILM 3HR INTERVAL # 2

      if t_stats_film2 > 34 then
        tt_wheat_stats_film2 = 0
      endif

      if t_stats_film2 >= 26 AND t_stats_film2 < 34 then
        tt_wheat_stats_film2 = 26 + -3.25 * (t_stats_film2 - 26)
      endif
```

```
if t_stats_film2 >= 0 AND t_stats_film2 < 26 then
  tt_wheat_stats_film2 = t_stats_film2
endif

if t_stats_film2 <0 then
  tt_wheat_stats_film2 = 0
endif

!    FILM 3HR INTERVAL # 3

if t_stats_film3 > 34 then
  tt_wheat_stats_film3 = 0
endif

if t_stats_film3 >= 26 AND t_stats_film3 < 34 then
  tt_wheat_stats_film3 = 26 + -3.25 * (t_stats_film3 - 26)
endif

if t_stats_film3 >= 0 AND t_stats_film3 < 26 then
  tt_wheat_stats_film3 = t_stats_film3
endif

if t_stats_film3 <0 then
  tt_wheat_stats_film3 = 0
endif

!    FILM 3HR INTERVAL # 4

if t_stats_film4 > 34 then
  tt_wheat_stats_film4 = 0
endif

if t_stats_film4 >= 26 AND t_stats_film4 < 34 then
  tt_wheat_stats_film4 = 26 + -3.25 * (t_stats_film4 - 26)
endif

if t_stats_film4 >= 0 AND t_stats_film4 < 26 then
  tt_wheat_stats_film4 = t_stats_film4
endif

if t_stats_film4 <0 then
  tt_wheat_stats_film4 = 0
endif
```

```
!     FILM 3HR INTERVAL # 5

      if t_stats_film5 > 34 then
        tt_wheat_stats_film5 = 0
      endif

      if t_stats_film5 >= 26 AND t_stats_film5 < 34 then
        tt_wheat_stats_film5 = 26 + -3.25 * (t_stats_film5 - 26)
      endif

      if t_stats_film5 >= 0 AND t_stats_film5 < 26 then
        tt_wheat_stats_film5 = t_stats_film5
      endif

      if t_stats_film5 <0 then
        tt_wheat_stats_film5 = 0
      endif

!     FILM 3HR INTERVAL # 6

      if t_stats_film6 > 34 then
        tt_wheat_stats_film6 = 0
      endif

      if t_stats_film6 >= 26 AND t_stats_film6 < 34 then
        tt_wheat_stats_film6 = 26 + -3.25 * (t_stats_film6 - 26)
      endif

      if t_stats_film6 >= 0 AND t_stats_film6 < 26 then
        tt_wheat_stats_film6 = t_stats_film6
      endif

      if t_stats_film6 <0 then
        tt_wheat_stats_film6 = 0
      endif

!     FILM 3HR INTERVAL # 7

      if t_stats_film7 > 34 then
        tt_wheat_stats_film7 = 0
      endif

      if t_stats_film7 >= 26 AND t_stats_film7 < 34 then
```

```
    tt_wheat_stats_film7 = 26 + -3.25 * (t_stats_film7 - 26)
  endif

  if t_stats_film7 >= 0 AND t_stats_film7 < 26 then
    tt_wheat_stats_film7 = t_stats_film7
  endif

  if t_stats_film7 <0 then
    tt_wheat_stats_film7 = 0
  endif

!    FILM 3HR INTERVAL # 8

  if t_stats_film8 > 34 then
    tt_wheat_stats_film8 = 0
  endif

  if t_stats_film8 >= 26 AND t_stats_film8 < 34 then
    tt_wheat_stats_film8 = 26 + -3.25 * (t_stats_film8 - 26)
  endif

  if t_stats_film8 >= 0 AND t_stats_film8 < 26 then
    tt_wheat_stats_film8 = t_stats_film8
  endif

  if t_stats_film8 <0 then
    tt_wheat_stats_film8 = 0
  endif

  tt_wheat_stats_film_average = (tt_wheat_stats_film1 + tt_wheat_stats_film2 +
tt_wheat_stats_film3 + tt_wheat_stats_film4 + tt_wheat_stats_film5 + tt_wheat_stats_film6 +
tt_wheat_stats_film7 + tt_wheat_stats_film8) / 8
!
!
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
!!!!!!!!!!!!!!!!!!!!!!  MAIZE HEAT STRESS  !!!!!!!!!!!!!!!!!!!!!!!!!!
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
!
!    AMBIENT 3HR INTERVAL # 1

  if t_ambient1 > 44 then
    hs_maize_ambient1 = 26
  endif
```

```
      if t_ambient1 >= 34 AND t_ambient1 < 44 then
        hs_maize_ambient1 = 2.6 * (t_ambient1 - 34)
      endif

      if t_ambient1 <34 then
        hs_maize_ambient1 = 0
      endif
!
!     AMBIENT 3HR INTERVAL # 2

      if t_ambient2 > 44 then
        hs_maize_ambient2 = 26
      endif

      if t_ambient2 >= 34 AND t_ambient2 < 44 then
        hs_maize_ambient2 = 2.6 * (t_ambient2 - 34)
      endif

      if t_ambient2 <34 then
        hs_maize_ambient2 = 0
      endif
!
!     AMBIENT 3HR INTERVAL # 3

      if t_ambient3 > 44 then
        hs_maize_ambient3 = 26
      endif

      if t_ambient3 >= 34 AND t_ambient3 < 44 then
        hs_maize_ambient3 = 2.6 * (t_ambient3 - 34)
      endif

      if t_ambient3 <34 then
        hs_maize_ambient3 = 0
      endif
!
!     AMBIENT 3HR INTERVAL # 4

      if t_ambient4 > 44 then
        hs_maize_ambient4 = 26
      endif

      if t_ambient4 >= 34 AND t_ambient4 < 44 then
        hs_maize_ambient4 = 2.6 * (t_ambient4 - 34)
```

```
      endif

      if t_ambient4 <34 then
        hs_maize_ambient4 = 0
      endif
!
!     AMBIENT 3HR INTERVAL # 5

      if t_ambient5 > 44 then
        hs_maize_ambient5 = 26
      endif

      if t_ambient5 >= 34 AND t_ambient5 < 44 then
        hs_maize_ambient5 = 2.6 * (t_ambient5 - 34)
      endif

      if t_ambient5 <34 then
        hs_maize_ambient5 = 0
      endif
!
!     AMBIENT 3HR INTERVAL # 6

      if t_ambient6 > 44 then
        hs_maize_ambient6 = 26
      endif

      if t_ambient6 >= 34 AND t_ambient6 < 44 then
        hs_maize_ambient6 = 2.6 * (t_ambient6 - 34)
      endif

      if t_ambient6 <34 then
        hs_maize_ambient6 = 0
      endif
!
!     AMBIENT 3HR INTERVAL # 7

      if t_ambient7 > 44 then
        hs_maize_ambient7 = 26
      endif

      if t_ambient7 >= 34 AND t_ambient7 < 44 then
        hs_maize_ambient7 = 2.6 * (t_ambient7 - 34)
      endif
```

```
      if t_ambient7 <34 then
        hs_maize_ambient7 = 0
      endif
!
!     AMBIENT 3HR INTERVAL # 8

      if t_ambient8 > 44 then
        hs_maize_ambient8 = 26
      endif

      if t_ambient8 >= 34 AND t_ambient8 < 44 then
        hs_maize_ambient8 = 2.6 * (t_ambient8 - 34)
      endif

      if t_ambient8 <34 then
        hs_maize_ambient8 = 0
      endif

      hs_maize_ambient_average = (hs_maize_ambient1 + hs_maize_ambient2 +
hs_maize_ambient3 + hs_maize_ambient4 + hs_maize_ambient5 + hs_maize_ambient6 +
hs_maize_ambient7 + hs_maize_ambient8) / 8
!
!
!
!     FILM 3HR INTERVAL – APSIM MODEL # 1

      if t_APSIM_film1 > 44 then
        hs_maize_APSIM_film1 = 26
      endif

      if t_APSIM_film1 >= 34 AND t_APSIM_film1 < 44 then
        hs_maize_APSIM_film1 = 2.6 * (t_APSIM_film1 - 34)
      endif

      if t_APSIM_film1 <34 then
        hs_maize_APSIM_film1 = 0
      endif
!
!     FILM 3HR INTERVAL – APSIM MODEL # 2

      if t_APSIM_film2 > 44 then
        hs_maize_APSIM_film2 = 26
      endif
```

```
      if t_APSIM_film2 >= 34 AND t_APSIM_film2 < 44 then
        hs_maize_APSIM_film2 = 2.6 * (t_APSIM_film2 - 34)
      endif

      if t_APSIM_film2 <34 then
        hs_maize_APSIM_film2 = 0
      endif
!
!     FILM 3HR INTERVAL – APSIM MODEL # 3

      if t_APSIM_film3 > 44 then
        hs_maize_APSIM_film3 = 26
      endif

      if t_APSIM_film3 >= 34 AND t_APSIM_film3 < 44 then
        hs_maize_APSIM_film3 = 2.6 * (t_APSIM_film3 - 34)
      endif

      if t_APSIM_film3 <34 then
        hs_maize_APSIM_film3 = 0
      endif
!
!     FILM 3HR INTERVAL – APSIM MODEL # 4

      if t_APSIM_film4 > 44 then
        hs_maize_APSIM_film4 = 26
      endif

      if t_APSIM_film4 >= 34 AND t_APSIM_film4 < 44 then
        hs_maize_APSIM_film4 = 2.6 * (t_APSIM_film4 - 34)
      endif

      if t_APSIM_film4 <34 then
        hs_maize_APSIM_film4 = 0
      endif
!
!     FILM 3HR INTERVAL – APSIM MODEL # 5

      if t_APSIM_film5 > 44 then
        hs_maize_APSIM_film5 = 26
      endif

      if t_APSIM_film5 >= 34 AND t_APSIM_film5 < 44 then
        hs_maize_APSIM_film5 = 2.6 * (t_APSIM_film5 - 34)
```

```
    endif

    if t_APSIM_film5 <34 then
      hs_maize_APSIM_film5 = 0
    endif
!
!   FILM 3HR INTERVAL – APSIM MODEL # 6

    if t_APSIM_film6 > 44 then
      hs_maize_APSIM_film6 = 26
    endif

    if t_APSIM_film6 >= 34 AND t_APSIM_film6 < 44 then
      hs_maize_APSIM_film6 = 2.6 * (t_APSIM_film6 - 34)
    endif

    if t_APSIM_film6 <34 then
      hs_maize_APSIM_film6 = 0
    endif
!
!   FILM 3HR INTERVAL – APSIM MODEL # 7

    if t_APSIM_film7 > 44 then
      hs_maize_APSIM_film7 = 26
    endif

    if t_APSIM_film7 >= 34 AND t_APSIM_film7 < 44 then
      hs_maize_APSIM_film7 = 2.6 * (t_APSIM_film7 - 34)
    endif

    if t_APSIM_film7 <34 then
      hs_maize_APSIM_film7 = 0
    endif
!
!   FILM 3HR INTERVAL – APSIM MODEL # 8

    if t_APSIM_film8 > 44 then
      hs_maize_APSIM_film8 = 26
    endif

    if t_APSIM_film8 >= 34 AND t_APSIM_film8 < 44 then
      hs_maize_APSIM_film8 = 2.6 * (t_APSIM_film8 - 34)
    endif
```

```
    if t_APSIM_film8 <34 then
      hs_maize_APSIM_film8 = 0
    endif

    hs_maize_APSIM_film_average = (hs_maize_APSIM_film1 + hs_maize_APSIM_film2
+ hs_maize_APSIM_film3 + hs_maize_APSIM_film4 + hs_maize_APSIM_film5 +
hs_maize_APSIM_film6 + hs_maize_APSIM_film7 + hs_maize_APSIM_film8) / 8

!
!
!    FILM 3HR INTERVAL – STATISTICAL MODEL # 1

    if t_stats_film1 > 44 then
      hs_maize_stats_film1 = 26
    endif

    if t_stats_film1 >= 34 AND t_stats_film1 < 44 then
      hs_maize_stats_film1 = 2.6 * (t_stats_film1 - 34)
    endif

    if t_stats_film1 <34 then
      hs_maize_stats_film1 = 0
    endif
!
!    FILM 3HR INTERVAL – STATISTICAL MODEL # 2

    if t_stats_film2 > 44 then
      hs_maize_stats_film2 = 26
    endif

    if t_stats_film2 >= 34 AND t_stats_film2 < 44 then
      hs_maize_stats_film2 = 2.6 * (t_stats_film2 - 34)
    endif

    if t_stats_film2 <34 then
      hs_maize_stats_film2 = 0
    endif
!
!    FILM 3HR INTERVAL – STATISTICAL MODEL # 3

    if t_stats_film3 > 44 then
      hs_maize_stats_film3 = 26
    endif
```

```
    if t_stats_film3 >= 34 AND t_stats_film3 < 44 then
      hs_maize_stats_film3 = 2.6 * (t_stats_film3 - 34)
    endif

    if t_stats_film3 <34 then
      hs_maize_stats_film3 = 0
    endif
!
!   FILM 3HR INTERVAL – STATISTICAL MODEL # 4

    if t_stats_film4 > 44 then
      hs_maize_stats_film4 = 26
    endif

    if t_stats_film4 >= 34 AND t_stats_film4 < 44 then
      hs_maize_stats_film4 = 2.6 * (t_stats_film4 - 34)
    endif

    if t_stats_film4 <34 then
      hs_maize_stats_film4 = 0
    endif
!
!   FILM 3HR INTERVAL – STATISTICAL MODEL # 5

    if t_stats_film5 > 44 then
      hs_maize_stats_film5 = 26
    endif

    if t_stats_film5 >= 34 AND t_stats_film5 < 44 then
      hs_maize_stats_film5 = 2.6 * (t_stats_film5 - 34)
    endif

    if t_stats_film5 <34 then
      hs_maize_stats_film5 = 0
    endif
!
!   FILM 3HR INTERVAL – STATISTICAL MODEL # 6

    if t_stats_film6 > 44 then
      hs_maize_stats_film6 = 26
    endif

    if t_stats_film6 >= 34 AND t_stats_film6 < 44 then
      hs_maize_stats_film6 = 2.6 * (t_stats_film6 - 34)
```

```
      endif

      if t_stats_film6 <34 then
        hs_maize_stats_film6 = 0
      endif
!
!     FILM 3HR INTERVAL – STATISTICAL MODEL # 7

      if t_stats_film7 > 44 then
        hs_maize_stats_film7 = 26
      endif

      if t_stats_film7 >= 34 AND t_stats_film7 < 44 then
        hs_maize_stats_film7 = 2.6 * (t_stats_film7 - 34)
      endif

      if t_stats_film7 <34 then
        hs_maize_stats_film7 = 0
      endif
!
!     FILM 3HR INTERVAL – STATISTICAL MODEL # 8

      if t_stats_film8 > 44 then
        hs_maize_stats_film8 = 26
      endif

      if t_stats_film8 >= 34 AND t_stats_film8 < 44 then
        hs_maize_stats_film8 = 2.6 * (t_stats_film8 - 34)
      endif

      if t_stats_film8 <34 then
        hs_maize_stats_film8 = 0
      endif

      hs_maize_stats_film_average = (hs_maize_stats_film1 + hs_maize_stats_film2 +
hs_maize_stats_film3 + hs_maize_stats_film4 + hs_maize_stats_film5 +
hs_maize_stats_film6 + hs_maize_stats_film7 + hs_maize_stats_film8) / 8
!
!
!
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
!!!!!!!!!!!!!!!!!!!!!!  WHEAT HEAT STRESS  !!!!!!!!!!!!!!!!!!!!!!!!!!
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
!
```

```
!    AMBIENT 3HR INTERVAL # 1

     if t_ambient1 > 34 then
       hs_wheat_ambient1 = 26
     endif

     if t_ambient1 >= 26 AND t_ambient1 < 34 then
       hs_wheat_ambient1 = 3.25 * (t_ambient1 - 26)
     endif

     if t_ambient1 <26 then
       hs_wheat_ambient1 = 0
     endif
!
!    AMBIENT 3HR INTERVAL # 2

     if t_ambient2 > 34 then
       hs_wheat_ambient2 = 26
     endif

     if t_ambient2 >= 26 AND t_ambient2 < 34 then
       hs_wheat_ambient2 = 3.25 * (t_ambient2 - 26)
     endif

     if t_ambient2 <26 then
       hs_wheat_ambient2 = 0
     endif
!
!    AMBIENT 3HR INTERVAL # 3

     if t_ambient3 > 34 then
       hs_wheat_ambient3 = 26
     endif

     if t_ambient3 >= 26 AND t_ambient3 < 34 then
       hs_wheat_ambient3 = 3.25 * (t_ambient3 - 26)
     endif

     if t_ambient3 <26 then
       hs_wheat_ambient3 = 0
     endif
!
!    AMBIENT 3HR INTERVAL # 4
```

```
      if t_ambient4 > 34 then
        hs_wheat_ambient4 = 26
      endif

      if t_ambient4 >= 26 AND t_ambient4 < 34 then
        hs_wheat_ambient4 = 3.25 * (t_ambient4 - 26)
      endif

      if t_ambient4 <26 then
        hs_wheat_ambient4 = 0
      endif
!
!     AMBIENT 3HR INTERVAL # 5

      if t_ambient5 > 34 then
        hs_wheat_ambient5 = 26
      endif

      if t_ambient5 >= 26 AND t_ambient5 < 34 then
        hs_wheat_ambient5 = 3.25 * (t_ambient5 - 26)
      endif

      if t_ambient5 <26 then
        hs_wheat_ambient5 = 0
      endif
!
!     AMBIENT 3HR INTERVAL # 6

      if t_ambient6 > 34 then
        hs_wheat_ambient6 = 26
      endif

      if t_ambient6 >= 26 AND t_ambient6 < 34 then
        hs_wheat_ambient6 = 3.25 * (t_ambient6 - 26)
      endif

      if t_ambient6 <26 then
        hs_wheat_ambient6 = 0
      endif
!
!     AMBIENT 3HR INTERVAL # 7

      if t_ambient7 > 34 then
        hs_wheat_ambient7 = 26
```

```
      endif

      if t_ambient7 >= 26 AND t_ambient7 < 34 then
        hs_wheat_ambient7 = 3.25 * (t_ambient7 - 26)
      endif

      if t_ambient7 <26 then
        hs_wheat_ambient7 = 0
      endif
!
!     AMBIENT 3HR INTERVAL # 8

      if t_ambient8 > 34 then
        hs_wheat_ambient8 = 26
      endif

      if t_ambient8 >= 26 AND t_ambient8 < 34 then
        hs_wheat_ambient8 = 3.25 * (t_ambient8 - 26)
      endif

      if t_ambient8 <26 then
        hs_wheat_ambient8 = 0
      endif

      hs_wheat_ambient_average = (hs_wheat_ambient1 + hs_wheat_ambient2 +
hs_wheat_ambient3 + hs_wheat_ambient4 + hs_wheat_ambient5 + hs_wheat_ambient6 +
hs_wheat_ambient7 + hs_wheat_ambient8) / 8
!
!
!
!     FILM 3HR INTERVAL – APSIM MODEL # 1

      if t_APSIM_film1 > 34 then
        hs_wheat_APSIM_film1 = 26
      endif

      if t_APSIM_film1 >= 26 AND t_APSIM_film1 < 34 then
        hs_wheat_APSIM_film1 = 3.25 * (t_APSIM_film1 - 26)
      endif

      if t_APSIM_film1 <26 then
        hs_wheat_APSIM_film1 = 0
      endif
!
```

```
!    FILM 3HR INTERVAL – APSIM MODEL # 2

     if t_APSIM_film2 > 34 then
       hs_wheat_APSIM_film2 = 26
     endif

     if t_APSIM_film2 >= 26 AND t_APSIM_film2 < 34 then
       hs_wheat_APSIM_film2 = 3.25 * (t_APSIM_film2 - 26)
     endif

     if t_APSIM_film2 <26 then
       hs_wheat_APSIM_film2 = 0
     endif
!
!    FILM 3HR INTERVAL – APSIM MODEL # 3

     if t_APSIM_film3 > 34 then
       hs_wheat_APSIM_film3 = 26
     endif

     if t_APSIM_film3 >= 26 AND t_APSIM_film3 < 34 then
       hs_wheat_APSIM_film3 = 3.25 * (t_APSIM_film3 - 26)
     endif

     if t_APSIM_film3 <26 then
       hs_wheat_APSIM_film3 = 0
     endif
!
!    FILM 3HR INTERVAL – APSIM MODEL # 4

     if t_APSIM_film4 > 34 then
       hs_wheat_APSIM_film4 = 26
     endif

     if t_APSIM_film4 >= 26 AND t_APSIM_film4 < 34 then
       hs_wheat_APSIM_film4 = 3.25 * (t_APSIM_film4 - 26)
     endif

     if t_APSIM_film4 <26 then
       hs_wheat_APSIM_film4 = 0
     endif
!
!    FILM 3HR INTERVAL – APSIM MODEL # 5
```

```
    if t_APSIM_film5 > 34 then
      hs_wheat_APSIM_film5 = 26
    endif

    if t_APSIM_film5 >= 26 AND t_APSIM_film5 < 34 then
      hs_wheat_APSIM_film5 = 3.25 * (t_APSIM_film5 - 26)
    endif

    if t_APSIM_film5 <26 then
      hs_wheat_APSIM_film5 = 0
    endif
!
!   FILM 3HR INTERVAL – APSIM MODEL # 6

    if t_APSIM_film6 > 34 then
      hs_wheat_APSIM_film6 = 26
    endif

    if t_APSIM_film6 >= 26 AND t_APSIM_film6 < 34 then
      hs_wheat_APSIM_film6 = 3.25 * (t_APSIM_film6 - 26)
    endif

    if t_APSIM_film6 <26 then
      hs_wheat_APSIM_film6 = 0
    endif
!
!   FILM 3HR INTERVAL – APSIM MODEL # 7

    if t_APSIM_film7 > 34 then
      hs_wheat_APSIM_film7 = 26
    endif

    if t_APSIM_film7 >= 26 AND t_APSIM_film7 < 34 then
      hs_wheat_APSIM_film7 = 3.25 * (t_APSIM_film7 - 26)
    endif

    if t_APSIM_film7 <26 then
      hs_wheat_APSIM_film7 = 0
    endif
!
!   FILM 3HR INTERVAL – APSIM MODEL # 8

    if t_APSIM_film8 > 34 then
      hs_wheat_APSIM_film8 = 26
```

```
    endif

    if t_APSIM_film8 >= 26 AND t_APSIM_film8 < 34 then
      hs_wheat_APSIM_film8 = 3.25 * (t_APSIM_film8 - 26)
    endif

    if t_APSIM_film8 <26 then
      hs_wheat_APSIM_film8 = 0
    endif

    hs_wheat_APSIM_film_average = (hs_wheat_APSIM_film1 + hs_wheat_APSIM_film2
+ hs_wheat_APSIM_film3 + hs_wheat_APSIM_film4 + hs_wheat_APSIM_film5 +
hs_wheat_APSIM_film6 + hs_wheat_APSIM_film7 + hs_wheat_APSIM_film8) / 8

!
!
!    FILM 3HR INTERVAL – STATISTICAL MODEL # 1

    if t_stats_film1 > 34 then
      hs_wheat_stats_film1 = 26
    endif

    if t_stats_film1 >= 26 AND t_stats_film1 < 34 then
      hs_wheat_stats_film1 = 3.25 * (t_stats_film1 - 26)
    endif

    if t_stats_film1 <26 then
      hs_wheat_stats_film1 = 0
    endif
!
!    FILM 3HR INTERVAL – STATISTICAL MODEL # 2

    if t_stats_film2 > 34 then
      hs_wheat_stats_film2 = 26
    endif

    if t_stats_film2 >= 26 AND t_stats_film2 < 34 then
      hs_wheat_stats_film2 = 3.25 * (t_stats_film2 - 26)
    endif

    if t_stats_film2 <26 then
      hs_wheat_stats_film2 = 0
    endif
!
```

```
!    FILM 3HR INTERVAL – STATISTICAL MODEL # 3

     if t_stats_film3 > 34 then
       hs_wheat_stats_film3 = 26
     endif

     if t_stats_film3 >= 26 AND t_stats_film3 < 34 then
       hs_wheat_stats_film3 = 3.25 * (t_stats_film3 - 26)
     endif

     if t_stats_film3 <26 then
       hs_wheat_stats_film3 = 0
     endif
!
!    FILM 3HR INTERVAL – STATISTICAL MODEL # 4

     if t_stats_film4 > 34 then
       hs_wheat_stats_film4 = 26
     endif

     if t_stats_film4 >= 26 AND t_stats_film4 < 34 then
       hs_wheat_stats_film4 = 3.25 * (t_stats_film4 - 26)
     endif

     if t_stats_film4 <26 then
       hs_wheat_stats_film4 = 0
     endif
!
!    FILM 3HR INTERVAL – STATISTICAL MODEL # 5

     if t_stats_film5 > 34 then
       hs_wheat_stats_film5 = 26
     endif

     if t_stats_film5 >= 26 AND t_stats_film5 < 34 then
       hs_wheat_stats_film5 = 3.25 * (t_stats_film5 - 26)
     endif

     if t_stats_film5 <26 then
       hs_wheat_stats_film5 = 0
     endif
!
!    FILM 3HR INTERVAL – STATISTICAL MODEL # 6
```

```
    if t_stats_film6 > 34 then
      hs_wheat_stats_film6 = 26
    endif

    if t_stats_film6 >= 26 AND t_stats_film6 < 34 then
      hs_wheat_stats_film6 = 3.25 * (t_stats_film6 - 26)
    endif

    if t_stats_film6 <26 then
      hs_wheat_stats_film6 = 0
    endif
!
!   FILM 3HR INTERVAL – STATISTICAL MODEL # 7

    if t_stats_film7 > 34 then
      hs_wheat_stats_film7 = 26
    endif

    if t_stats_film7 >= 26 AND t_stats_film7 < 34 then
      hs_wheat_stats_film7 = 3.25 * (t_stats_film7 - 26)
    endif

    if t_stats_film7 <26 then
      hs_wheat_stats_film7 = 0
    endif
!
!   FILM 3HR INTERVAL – STATISTICAL MODEL # 8

    if t_stats_film8 > 34 then
      hs_wheat_stats_film8 = 26
    endif

    if t_stats_film8 >= 26 AND t_stats_film8 < 34 then
      hs_wheat_stats_film8 = 3.25 * (t_stats_film8 - 26)
    endif

    if t_stats_film8 <26 then
      hs_wheat_stats_film8 = 0
    endif

    hs_wheat_stats_film_average = (hs_wheat_stats_film1 + hs_wheat_stats_film2 +
hs_wheat_stats_film3 + hs_wheat_stats_film4 + hs_wheat_stats_film5 +
hs_wheat_stats_film6 + hs_wheat_stats_film7 + hs_wheat_stats_film8) / 8
!
```

```
!
!
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
!!!!!!!!!!!!!!!!!!!!!!!!  MAIZE COLD LIMITED  !!!!!!!!!!!!!!!!!!!!!!!!!!!
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
!
!     AMBIENT 3HR INTERVAL # 1

      if t_ambient1 >= 34 then
        cl_maize_ambient1 = 0
      endif

      if t_ambient1 >= 18 AND t_ambient1 < 34 then
        cl_maize_ambient1 = 34 - t_ambient1
      endif

      if t_ambient1 >= 0 AND t_ambient1 < 18 then
        cl_maize_ambient1 = 10 + 5 * (18 - t_ambient1) / 9
      endif

      if t_ambient1 < 0 then
        cl_maize_ambient1 = 26
      endif

!     AMBIENT 3HR INTERVAL # 2

      if t_ambient2 >= 34 then
        cl_maize_ambient2 = 0
      endif

      if t_ambient2 >= 18 AND t_ambient2 < 34 then
        cl_maize_ambient2 = 34 - t_ambient2
      endif

      if t_ambient2 >= 0 AND t_ambient2 < 18 then
        cl_maize_ambient2 = 10 + 5 * (18 - t_ambient2) / 9
      endif

      if t_ambient2 < 0 then
        cl_maize_ambient2 = 26
      endif

!     AMBIENT 3HR INTERVAL # 3
```

```
if t_ambient3 >= 34 then
  cl_maize_ambient3 = 0
endif

if t_ambient3 >= 18 AND t_ambient3 < 34 then
  cl_maize_ambient3 = 34 - t_ambient3
endif

if t_ambient3 >= 0 AND t_ambient3 < 18 then
  cl_maize_ambient3 = 10 + 5 * (18 - t_ambient3) / 9
endif
if t_ambient3 < 0 then
  cl_maize_ambient3 = 26
endif

!    AMBIENT 3HR INTERVAL # 4

if t_ambient4 >= 34 then
  cl_maize_ambient4 = 0
endif

if t_ambient4 >= 18 AND t_ambient4 < 34 then
  cl_maize_ambient4 = 34 - t_ambient4
endif

if t_ambient4 >= 0 AND t_ambient4 < 18 then
  cl_maize_ambient4 = 10 + 5 * (18 - t_ambient4) / 9
endif

if t_ambient4 < 0 then
  cl_maize_ambient4 = 26
endif

!    AMBIENT 3HR INTERVAL # 5

if t_ambient5 >= 34 then
  cl_maize_ambient5 = 0
endif

if t_ambient5 >= 18 AND t_ambient5 < 34 then
  cl_maize_ambient5 = 34 - t_ambient5
endif

if t_ambient5 >= 0 AND t_ambient5 < 18 then
```

```
    cl_maize_ambient5 = 10 + 5 * (18 - t_ambient5) / 9
  endif

  if t_ambient5 < 0 then
    cl_maize_ambient5 = 26
  endif

!   AMBIENT 3HR INTERVAL # 6

  if t_ambient6 >= 34 then
    cl_maize_ambient6 = 0
  endif

  if t_ambient6 >= 18 AND t_ambient6 < 34 then
    cl_maize_ambient6 = 34 - t_ambient6
  endif

  if t_ambient6 >= 0 AND t_ambient6 < 18 then
    cl_maize_ambient6 = 10 + 5 * (18 - t_ambient6) / 9
  endif

  if t_ambient6 < 0 then
    cl_maize_ambient6 = 26
  endif

!   AMBIENT 3HR INTERVAL # 7

  if t_ambient7 >= 34 then
    cl_maize_ambient7 = 0
  endif

  if t_ambient7 >= 18 AND t_ambient7 < 34 then
    cl_maize_ambient7 = 34 - t_ambient7
  endif

  if t_ambient7 >= 0 AND t_ambient7 < 18 then
    cl_maize_ambient7 = 10 + 5 * (18 - t_ambient7) / 9
  endif

  if t_ambient7 < 0 then
    cl_maize_ambient7 = 26
  endif

!   AMBIENT 3HR INTERVAL # 8
```

```
      if t_ambient8 >= 34 then
        cl_maize_ambient8 = 0
      endif

      if t_ambient8 >= 18 AND t_ambient8 < 34 then
        cl_maize_ambient8 = 34 - t_ambient8
      endif

      if t_ambient8 >= 0 AND t_ambient8 < 18 then
        cl_maize_ambient8 = 10 + 5 * (18 - t_ambient8) / 9
      endif

      if t_ambient8 < 0 then
        cl_maize_ambient8 = 26
      endif

      cl_maize_ambient_average = (cl_maize_ambient1 + cl_maize_ambient2 +
cl_maize_ambient3 + cl_maize_ambient4 + cl_maize_ambient5 + cl_maize_ambient6 +
cl_maize_ambient7 + cl_maize_ambient8) / 8

!     FILM 3HR INTERVAL – APSIM MODEL # 1

      if t_APSIM_film1 >= 34 then
        cl_maize_APSIM_film1 = 0
      endif

      if t_APSIM_film1 >= 18 AND t_APSIM_film1 < 34 then
        cl_maize_APSIM_film1 = 34 - t_APSIM_film1
      endif

      if t_APSIM_film1 >= 0 AND t_APSIM_film1 < 18 then
        cl_maize_APSIM_film1 = 10 + 5 * (18 - t_APSIM_film1) / 9
      endif

      if t_APSIM_film1 < 0 then
        cl_maize_APSIM_film1 = 26
      endif

!     FILM 3HR INTERVAL – APSIM MODEL # 2

      if t_APSIM_film2 >= 34 then
        cl_maize_APSIM_film2 = 0
      endif
```

```
      if t_APSIM_film2 >= 18 AND t_APSIM_film2 < 34 then
        cl_maize_APSIM_film2 = 34 - t_APSIM_film2
      endif

      if t_APSIM_film2 >= 0 AND t_APSIM_film2 < 18 then
        cl_maize_APSIM_film2 = 10 + 5 * (18 - t_APSIM_film2) / 9
      endif

      if t_APSIM_film2 < 0 then
        cl_maize_APSIM_film2 = 26
      endif

!     FILM 3HR INTERVAL – APSIM MODEL # 3

      if t_APSIM_film3 >= 34 then
        cl_maize_APSIM_film3 = 0
      endif

      if t_APSIM_film3 >= 18 AND t_APSIM_film3 < 34 then
        cl_maize_APSIM_film3 = 34 - t_APSIM_film3
      endif

      if t_APSIM_film3 >= 0 AND t_APSIM_film3 < 18 then
        cl_maize_APSIM_film3 = 10 + 5 * (18 - t_APSIM_film3) / 9
      endif

      if t_APSIM_film3 < 0 then
        cl_maize_APSIM_film3 = 26
      endif

!     FILM 3HR INTERVAL – APSIM MODEL # 4

      if t_APSIM_film4 >= 34 then
        cl_maize_APSIM_film4 = 0
      endif

      if t_APSIM_film4 >= 18 AND t_APSIM_film4 < 34 then
        cl_maize_APSIM_film4 = 34 - t_APSIM_film4
      endif

      if t_APSIM_film4 >= 0 AND t_APSIM_film4 < 18 then
        cl_maize_APSIM_film4 = 10 + 5 * (18 - t_APSIM_film4) / 9
      endif
```

```
    if t_APSIM_film4 < 0 then
      cl_maize_APSIM_film4 = 26
    endif

!   FILM 3HR INTERVAL – APSIM MODEL # 5

    if t_APSIM_film5 >= 34 then
      cl_maize_APSIM_film5 = 0
    endif

    if t_APSIM_film5 >= 18 AND t_APSIM_film5 < 34 then
      cl_maize_APSIM_film5 = 34 - t_APSIM_film5
    endif

    if t_APSIM_film5 >= 0 AND t_APSIM_film5 < 18 then
      cl_maize_APSIM_film5 = 10 + 5 * (18 - t_APSIM_film5) / 9
    endif

    if t_APSIM_film5 < 0 then
      cl_maize_APSIM_film5 = 26
    endif

!   FILM 3HR INTERVAL – APSIM MODEL # 6

    if t_APSIM_film6 >= 34 then
      cl_maize_APSIM_film6 = 0
    endif

    if t_APSIM_film6 >= 18 AND t_APSIM_film6 < 34 then
      cl_maize_APSIM_film6 = 34 - t_APSIM_film6
    endif

    if t_APSIM_film6 >= 0 AND t_APSIM_film6 < 18 then
      cl_maize_APSIM_film6 = 10 + 5 * (18 - t_APSIM_film6) / 9
    endif

    if t_APSIM_film6 < 0 then
      cl_maize_APSIM_film6 = 26
    endif

!   FILM 3HR INTERVAL – APSIM MODEL # 7

    if t_APSIM_film7 >= 34 then
```

```
    cl_maize_APSIM_film7 = 0
  endif

  if t_APSIM_film7 >= 18 AND t_APSIM_film7 < 34 then
    cl_maize_APSIM_film7 = 34 - t_APSIM_film7
  endif

  if t_APSIM_film7 >= 0 AND t_APSIM_film7 < 18 then
    cl_maize_APSIM_film7 = 10 + 5 * (18 - t_APSIM_film7) / 9
  endif

  if t_APSIM_film7 < 0 then
    cl_maize_APSIM_film7 = 26
  endif

!    FILM 3HR INTERVAL – APSIM MODEL # 8

  if t_APSIM_film8 >= 34 then
    cl_maize_APSIM_film8 = 0
  endif

  if t_APSIM_film8 >= 18 AND t_APSIM_film8 < 34 then
    cl_maize_APSIM_film8 = 34 - t_APSIM_film8
  endif

  if t_APSIM_film8 >= 0 AND t_APSIM_film8 < 18 then
    cl_maize_APSIM_film8 = 10 + 5 * (18 - t_APSIM_film8) / 9
  endif

  if t_APSIM_film8 < 0 then
    cl_maize_APSIM_film8 = 26
  endif

  cl_maize_APSIM_film_average = (cl_maize_APSIM_film1 + cl_maize_APSIM_film2 +
cl_maize_APSIM_film3 + cl_maize_APSIM_film4 + cl_maize_APSIM_film5 +
cl_maize_APSIM_film6 + cl_maize_APSIM_film7 + cl_maize_APSIM_film8) / 8

!    FILM 3HR INTERVAL – STATISTICAL MODEL # 1

  if t_stats_film1 >= 34 then
    cl_maize_stats_film1 = 0
  endif

  if t_stats_film1 >= 18 AND t_stats_film1 < 34 then
```

```
    cl_maize_stats_film1 = 34 - t_stats_film1
  endif

  if t_stats_film1 >= 0 AND t_stats_film1 < 18 then
    cl_maize_stats_film1 = 10 + 5 * (18 - t_stats_film1) / 9
  endif

  if t_stats_film1 < 0 then
    cl_maize_stats_film1 = 26
  endif

!   FILM 3HR INTERVAL – STATISTICAL MODEL # 2

  if t_stats_film2 >= 34 then
    cl_maize_stats_film2 = 0
  endif

  if t_stats_film2 >= 18 AND t_stats_film2 < 34 then
    cl_maize_stats_film2 = 34 - t_stats_film2
  endif

  if t_stats_film2 >= 0 AND t_stats_film2 < 18 then
    cl_maize_stats_film2 = 10 + 5 * (18 - t_stats_film2) / 9
  endif

  if t_stats_film2 < 0 then
    cl_maize_stats_film2 = 26
  endif

!   FILM 3HR INTERVAL – STATISTICAL MODEL # 3

  if t_stats_film3 >= 34 then
    cl_maize_stats_film3 = 0
  endif

  if t_stats_film3 >= 18 AND t_stats_film3 < 34 then
    cl_maize_stats_film3 = 34 - t_stats_film3
  endif

  if t_stats_film3 >= 0 AND t_stats_film3 < 18 then
    cl_maize_stats_film3 = 10 + 5 * (18 - t_stats_film3) / 9
  endif

  if t_stats_film3 < 0 then
```

```
      cl_maize_stats_film3 = 26
    endif

!   FILM 3HR INTERVAL – STATISTICAL MODEL # 4

    if t_stats_film4 >= 34 then
      cl_maize_stats_film4 = 0
    endif

    if t_stats_film4 >= 18 AND t_stats_film4 < 34 then
      cl_maize_stats_film4 = 34 - t_stats_film4
    endif

    if t_stats_film4 >= 0 AND t_stats_film4 < 18 then
      cl_maize_stats_film4 = 10 + 5 * (18 - t_stats_film4) / 9
    endif

    if t_stats_film4 < 0 then
      cl_maize_stats_film4 = 26
    endif

!   FILM 3HR INTERVAL – STATISTICAL MODEL # 5

    if t_stats_film5 >= 34 then
      cl_maize_stats_film5 = 0
    endif

    if t_stats_film5 >= 18 AND t_stats_film5 < 34 then
      cl_maize_stats_film5 = 34 - t_stats_film5
    endif

    if t_stats_film5 >= 0 AND t_stats_film5 < 18 then
      cl_maize_stats_film5 = 10 + 5 * (18 - t_stats_film5) / 9
    endif

    if t_stats_film5 < 0 then
      cl_maize_stats_film5 = 26
    endif

!   FILM 3HR INTERVAL – STATISTICAL MODEL # 6

    if t_stats_film6 >= 34 then
      cl_maize_stats_film6 = 0
    endif
```

```
    if t_stats_film6 >= 18 AND t_stats_film6 < 34 then
      cl_maize_stats_film6 = 34 - t_stats_film6
    endif

    if t_stats_film6 >= 0 AND t_stats_film6 < 18 then
      cl_maize_stats_film6 = 10 + 5 * (18 - t_stats_film6) / 9
    endif

    if t_stats_film6 < 0 then
      cl_maize_stats_film6 = 26
    endif

!   FILM 3HR INTERVAL – STATISTICAL MODEL # 7

    if t_stats_film7 >= 34 then
      cl_maize_stats_film7 = 0
    endif

    if t_stats_film7 >= 18 AND t_stats_film7 < 34 then
      cl_maize_stats_film7 = 34 - t_stats_film7
    endif

    if t_stats_film7 >= 0 AND t_stats_film7 < 18 then
      cl_maize_stats_film7 = 10 + 5 * (18 - t_stats_film7) / 9
    endif

    if t_stats_film7 < 0 then
      cl_maize_stats_film7 = 26
    endif

!   FILM 3HR INTERVAL – STATISTICAL MODEL # 8

    if t_stats_film8 >= 34 then
      cl_maize_stats_film8 = 0
    endif

    if t_stats_film8 >= 18 AND t_stats_film8 < 34 then
      cl_maize_stats_film8 = 34 - t_stats_film8
    endif

    if t_stats_film8 >= 0 AND t_stats_film8 < 18 then
      cl_maize_stats_film8 = 10 + 5 * (18 - t_stats_film8) / 9
    endif
```

```
      if t_stats_film8 < 0 then
        cl_maize_stats_film8 = 26
      endif

      cl_maize_stats_film_average = (cl_maize_stats_film1 + cl_maize_stats_film2 +
cl_maize_stats_film3 + cl_maize_stats_film4 + cl_maize_stats_film5 + cl_maize_stats_film6
+ cl_maize_stats_film7 + cl_maize_stats_film8) / 8

!
!
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
!!!!!!!!!!!!!!!!!!!!!!!  WHEAT COLD LIMITED  !!!!!!!!!!!!!!!!!!!!!!!!!!
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
!
!     AMBIENT 3HR INTERVAL # 1

      if t_ambient1 >= 26 then
        cl_wheat_ambient1 = 0
      endif

      if t_ambient1 >= 0 AND t_ambient1 < 26 then
        cl_wheat_ambient1 = 26 - t_ambient1
      endif

      if t_ambient1 < 0 then
        cl_wheat_ambient1 = 26
      endif
!
!     AMBIENT 3HR INTERVAL # 2

      if t_ambient2 >= 26 then
        cl_wheat_ambient2 = 0
      endif

      if t_ambient2 >= 0 AND t_ambient2 < 26 then
        cl_wheat_ambient2 = 26 - t_ambient2
      endif

      if t_ambient2 < 0 then
        cl_wheat_ambient2 = 26
      endif
!
!     AMBIENT 3HR INTERVAL # 3
```

```
    if t_ambient3 >= 26 then
      cl_wheat_ambient3 = 0
    endif

    if t_ambient3 >= 0 AND t_ambient3 < 26 then
      cl_wheat_ambient3 = 26 - t_ambient3
    endif

    if t_ambient3 < 0 then
      cl_wheat_ambient3 = 26
    endif
!
!   AMBIENT 3HR INTERVAL # 4

    if t_ambient4 >= 26 then
      cl_wheat_ambient4 = 0
    endif

    if t_ambient4 >= 0 AND t_ambient4 < 26 then
      cl_wheat_ambient4 = 26 - t_ambient4
    endif

    if t_ambient4 < 0 then
      cl_wheat_ambient4 = 26
    endif
!
!   AMBIENT 3HR INTERVAL # 5

    if t_ambient5 >= 26 then
      cl_wheat_ambient5 = 0
    endif

    if t_ambient5 >= 0 AND t_ambient5 < 26 then
      cl_wheat_ambient5 = 26 - t_ambient5
    endif

    if t_ambient5 < 0 then
      cl_wheat_ambient5 = 26
    endif
!
!   AMBIENT 3HR INTERVAL # 6

    if t_ambient6 >= 26 then
```

```
      cl_wheat_ambient6 = 0
    endif

    if t_ambient6 >= 0 AND t_ambient6 < 26 then
      cl_wheat_ambient6 = 26 - t_ambient6
    endif

    if t_ambient6 < 0 then
      cl_wheat_ambient6 = 26
    endif
!
!   AMBIENT 3HR INTERVAL # 7

    if t_ambient7 >= 26 then
      cl_wheat_ambient7 = 0
    endif

    if t_ambient7 >= 0 AND t_ambient7 < 26 then
      cl_wheat_ambient7 = 26 - t_ambient7
    endif

    if t_ambient7 < 0 then
      cl_wheat_ambient7 = 26
    endif
!
!   AMBIENT 3HR INTERVAL # 8

    if t_ambient8 >= 26 then
      cl_wheat_ambient8 = 0
    endif

    if t_ambient8 >= 0 AND t_ambient8 < 26 then
      cl_wheat_ambient8 = 26 - t_ambient8
    endif

    if t_ambient8 < 0 then
      cl_wheat_ambient8 = 26
    endif

    cl_wheat_ambient_average = (cl_wheat_ambient1 + cl_wheat_ambient2 +
cl_wheat_ambient3 + cl_wheat_ambient4 + cl_wheat_ambient5 + cl_wheat_ambient6 +
cl_wheat_ambient7 + cl_wheat_ambient8) / 8
!
!
```

```
!
!    FILM 3HR INTERVAL – APSIM MODEL # 1

     if t_APSIM_film1 >= 26 then
       cl_wheat_APSIM_film1 = 0
     endif

     if t_APSIM_film1 >= 0 AND t_APSIM_film1 < 26 then
       cl_wheat_APSIM_film1 = 26 - t_APSIM_film1
     endif

     if t_APSIM_film1 < 0 then
       cl_wheat_APSIM_film1 = 26
     endif
!
!    FILM 3HR INTERVAL – APSIM MODEL # 2

     if t_APSIM_film2 >= 26 then
       cl_wheat_APSIM_film2 = 0
     endif

     if t_APSIM_film2 >= 0 AND t_APSIM_film2 < 26 then
       cl_wheat_APSIM_film2 = 26 - t_APSIM_film2
     endif

     if t_APSIM_film2 < 0 then
       cl_wheat_APSIM_film2 = 26
     endif
!
!    FILM 3HR INTERVAL – APSIM MODEL # 3

     if t_APSIM_film3 >= 26 then
       cl_wheat_APSIM_film3 = 0
     endif

     if t_APSIM_film3 >= 0 AND t_APSIM_film3 < 26 then
       cl_wheat_APSIM_film3 = 26 - t_APSIM_film3
     endif

     if t_APSIM_film3 < 0 then
       cl_wheat_APSIM_film3 = 26
     endif
!
!    FILM 3HR INTERVAL – APSIM MODEL # 4
```

```
      if t_APSIM_film4 >= 26 then
        cl_wheat_APSIM_film4 = 0
      endif

      if t_APSIM_film4 >= 0 AND t_APSIM_film4 < 26 then
        cl_wheat_APSIM_film4 = 26 - t_APSIM_film4
      endif

      if t_APSIM_film4 < 0 then
        cl_wheat_APSIM_film4 = 26
      endif
!
!     FILM 3HR INTERVAL – APSIM MODEL # 5

      if t_APSIM_film5 >= 26 then
        cl_wheat_APSIM_film5 = 0
      endif

      if t_APSIM_film5 >= 0 AND t_APSIM_film5 < 26 then
        cl_wheat_APSIM_film5 = 26 - t_APSIM_film5
      endif

      if t_APSIM_film5 < 0 then
        cl_wheat_APSIM_film5 = 26
      endif
!
!     FILM 3HR INTERVAL – APSIM MODEL # 6

      if t_APSIM_film6 >= 26 then
        cl_wheat_APSIM_film6 = 0
      endif

      if t_APSIM_film6 >= 0 AND t_APSIM_film6 < 26 then
        cl_wheat_APSIM_film6 = 26 - t_APSIM_film6
      endif

      if t_APSIM_film6 < 0 then
        cl_wheat_APSIM_film6 = 26
      endif
!
!     FILM 3HR INTERVAL – APSIM MODEL # 7

      if t_APSIM_film7 >= 26 then
```

```
    cl_wheat_APSIM_film7 = 0
  endif

  if t_APSIM_film7 >= 0 AND t_APSIM_film7 < 26 then
    cl_wheat_APSIM_film7 = 26 - t_APSIM_film7
  endif

  if t_APSIM_film7 < 0 then
    cl_wheat_APSIM_film7 = 26
  endif
!
!    FILM 3HR INTERVAL – APSIM MODEL # 8

  if t_APSIM_film8 >= 26 then
    cl_wheat_APSIM_film8 = 0
  endif

  if t_APSIM_film8 >= 0 AND t_APSIM_film8 < 26 then
    cl_wheat_APSIM_film8 = 26 - t_APSIM_film8
  endif

  if t_APSIM_film8 < 0 then
    cl_wheat_APSIM_film8 = 26
  endif

  cl_wheat_APSIM_film_average = (cl_wheat_APSIM_film1 + cl_wheat_APSIM_film2 +
cl_wheat_APSIM_film3 + cl_wheat_APSIM_film4 + cl_wheat_APSIM_film5 +
cl_wheat_APSIM_film6 + cl_wheat_APSIM_film7 + cl_wheat_APSIM_film8) / 8

!
!
!    FILM 3HR INTERVAL – STATISTICAL MODEL # 1

  if t_stats_film1 >= 26 then
    cl_wheat_stats_film1 = 0
  endif

  if t_stats_film1 >= 0 AND t_stats_film1 < 26 then
    cl_wheat_stats_film1 = 26 - t_stats_film1
  endif

  if t_stats_film1 < 0 then
    cl_wheat_stats_film1 = 26
  endif
```

```
!
!    FILM 3HR INTERVAL – STATISTICAL MODEL # 2

     if t_stats_film2 >= 26 then
       cl_wheat_stats_film2 = 0
     endif

     if t_stats_film2 >= 0 AND t_stats_film2 < 26 then
       cl_wheat_stats_film2 = 26 - t_stats_film2
     endif

     if t_stats_film2 < 0 then
       cl_wheat_stats_film2 = 26
     endif
!
!    FILM 3HR INTERVAL – STATISTICAL MODEL # 3

     if t_stats_film3 >= 26 then
       cl_wheat_stats_film3 = 0
     endif

     if t_stats_film3 >= 0 AND t_stats_film3 < 26 then
       cl_wheat_stats_film3 = 26 - t_stats_film3
     endif

     if t_stats_film3 < 0 then
       cl_wheat_stats_film3 = 26
     endif
!
!    FILM 3HR INTERVAL – STATISTICAL MODEL # 4

     if t_stats_film4 >= 26 then
       cl_wheat_stats_film4 = 0
     endif

     if t_stats_film4 >= 0 AND t_stats_film4 < 26 then
       cl_wheat_stats_film4 = 26 - t_stats_film4
     endif

     if t_stats_film4 < 0 then
       cl_wheat_stats_film4 = 26
     endif
!
!    FILM 3HR INTERVAL – STATISTICAL MODEL # 5
```

```
     if t_stats_film5 >= 26 then
       cl_wheat_stats_film5 = 0
     endif

     if t_stats_film5 >= 0 AND t_stats_film5 < 26 then
       cl_wheat_stats_film5 = 26 - t_stats_film5
     endif

     if t_stats_film5 < 0 then
       cl_wheat_stats_film5 = 26
     endif
!
!    FILM 3HR INTERVAL – STATISTICAL MODEL # 6

     if t_stats_film6 >= 26 then
       cl_wheat_stats_film6 = 0
     endif

     if t_stats_film6 >= 0 AND t_stats_film6 < 26 then
       cl_wheat_stats_film6 = 26 - t_stats_film6
     endif

     if t_stats_film6 < 0 then
       cl_wheat_stats_film6 = 26
     endif
!
!    FILM 3HR INTERVAL – STATISTICAL MODEL # 7

     if t_stats_film7 >= 26 then
       cl_wheat_stats_film7 = 0
     endif

     if t_stats_film7 >= 0 AND t_stats_film7 < 26 then
       cl_wheat_stats_film7 = 26 - t_stats_film7
     endif

     if t_stats_film7 < 0 then
       cl_wheat_stats_film7 = 26
     endif
!
!    FILM 3HR INTERVAL – STATISTICAL MODEL # 8

     if t_stats_film8 >= 26 then
```

```
    cl_wheat_stats_film8 = 0
  endif

  if t_stats_film8 >= 0 AND t_stats_film8 < 26 then
    cl_wheat_stats_film8 = 26 - t_stats_film8
  endif

  if t_stats_film8 < 0 then
    cl_wheat_stats_film8 = 26
  endif

  cl_wheat_stats_film_average = (cl_wheat_stats_film1 + cl_wheat_stats_film2 +
cl_wheat_stats_film3 + cl_wheat_stats_film4 + cl_wheat_stats_film5 + cl_wheat_stats_film6
+ cl_wheat_stats_film7 + cl_wheat_stats_film8) / 8
```